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MIAPP Munich Institute for Astro- and Particle Physics

JÜLICH FORSCHUNGSZENTRUM

Search for permanent electric dipole moments

June 03, 2015

Frank Rathmann

Flavour 2015: New Physics at High Energy and High Precision, MIAPP

Outline

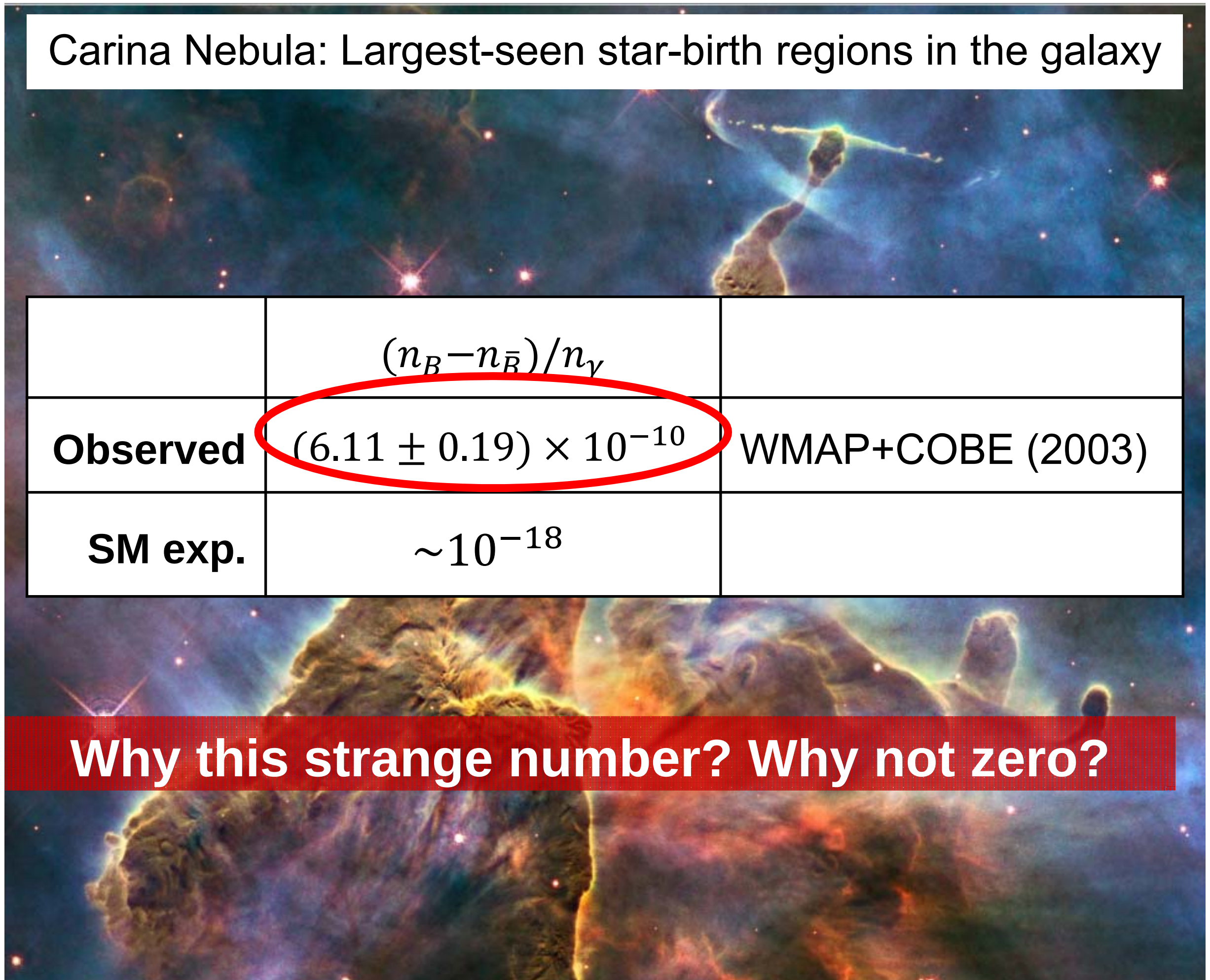
- Introduction
  - Baryogenesis, EDMs & present limits
- EDM search using storage rings
  - Recent progress
    - Spin coherence time
    - Spin tune measurement
    - First direct p, d EDM measurement
    - Role of magnetic machine imperfections
- Technical developments
  - Electrostatic deflectors
- Conclusion

Unsolved Mysteries: Beyond the Standard Model

1. Why do we observe matter and almost no antimatter if we believe there is a symmetry between the two in the universe?
2. What is this "dark matter" that we can't see that has visible gravitational effects in the cosmos?
3. Why can't the Standard Model predict a particle's mass?
4. Are quarks and leptons actually fundamental, or made up of even more fundamental particles?
5. Why are there exactly three generations of quarks and leptons? How does gravity fit into all of this?

From http://particleadventure.org/beyond_start.html

Physics: Observed Baryon Asymmetry



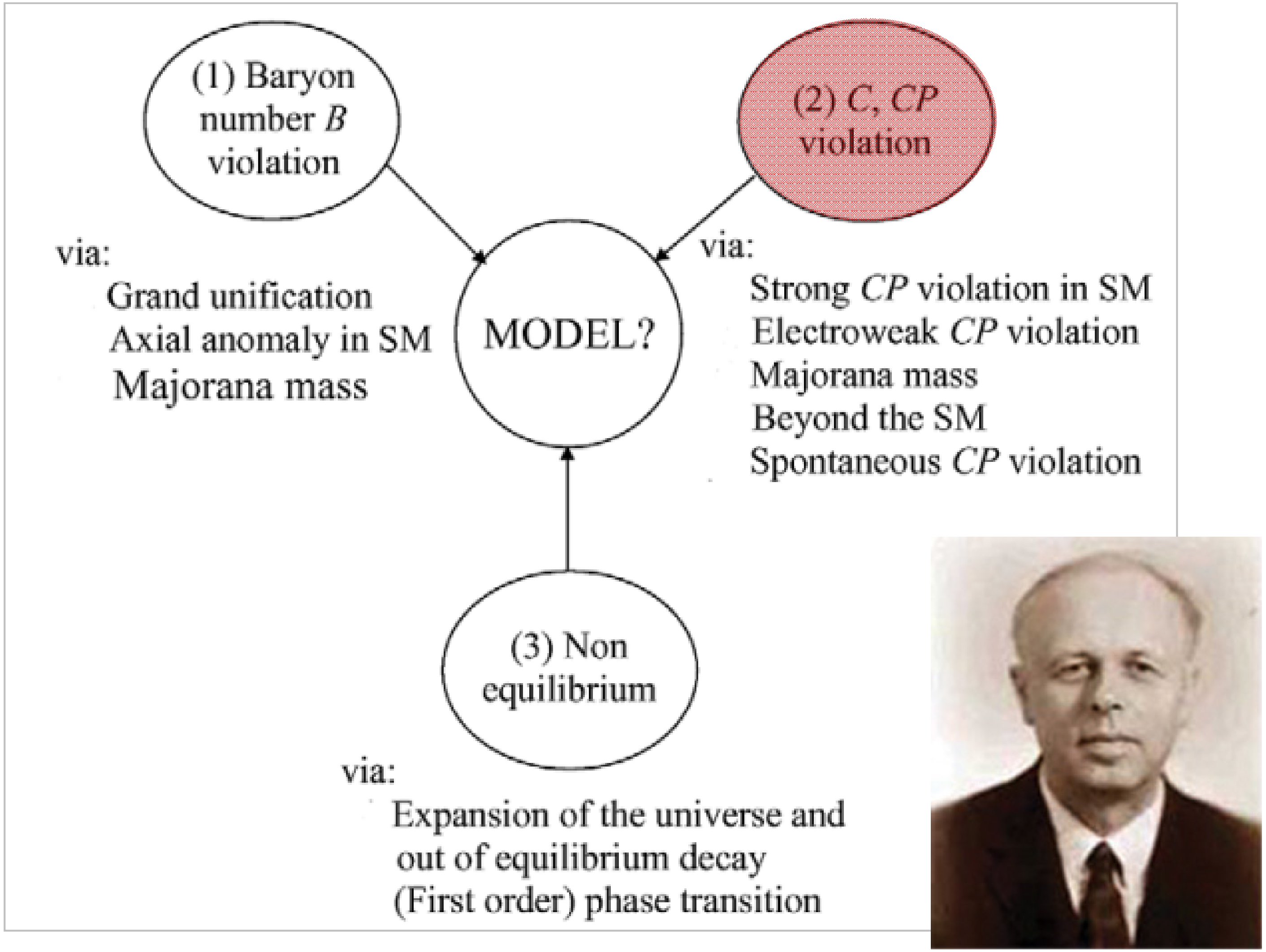
Carina Nebula: Largest-seen star-birth regions in the galaxy

	$(n_B - n_{\bar{B}})/n_\gamma$	
Observed	$(6.11 \pm 0.19) \times 10^{-10}$	WMAP+COBE (2003)
SM exp.	$\sim 10^{-18}$	

Why this strange number? Why not zero?

- Search for new physics beyond the standard model
- Mystery of **missing antimatter** addresses the puzzle of our existence

Physics: Baryogenesis



(1967)

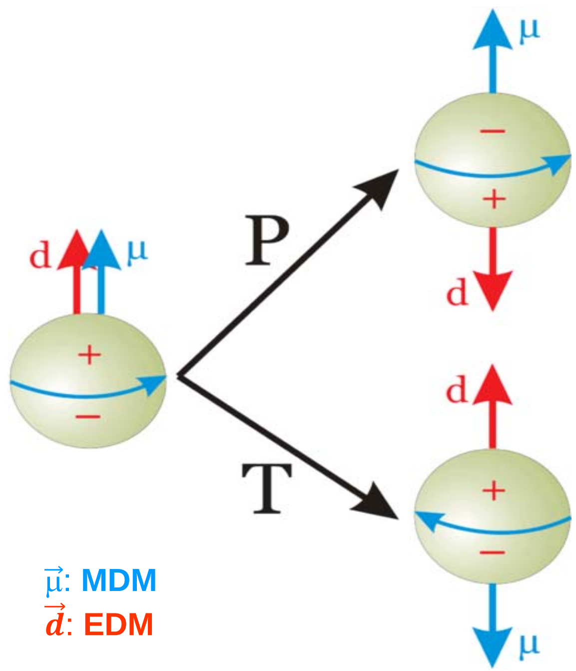
Ingredients for baryogenesis: **3 Sakharov conditions**

EDMs: Discrete Symmetries

Not Charge symmetric

$\vec{d}$ (aligned with spin)

EDM: $\vec{d} = \sum \vec{r}_i e_i \xrightarrow[\text{subatomic}]{} d \cdot \vec{S}/S$



$\vec{\mu}$: MDM
$\vec{d}$: EDM

$$\mathcal{H} = -\mu \frac{\vec{S}}{S} \cdot \vec{B} - d \frac{\vec{S}}{S} \cdot \vec{E}$$

P: $$\mathcal{H} = -\mu \frac{\vec{S}}{S} \cdot \vec{B} + d \frac{\vec{S}}{S} \cdot \vec{\boldsymbol{E}}$$

T: $$\mathcal{H} = -\mu \frac{\vec{S}}{S} \cdot \vec{B} + d \frac{\vec{S}}{S} \cdot \vec{\boldsymbol{E}}$$

Permanent EDMs violate both P and T symmetry.
Assuming CPT to hold, CP violated also.

EDMs: Naive estimate of the nucleon EDM scale

Khriplovich & Lamoreux (1997); Nikolaev (2012)

- $\boldsymbol{CP}$ & $\boldsymbol{P}$ conserving magnetic moment ≈ nuclear magneton $\boldsymbol{\mu_N}$

$$\mu_N = \frac{e}{2m_p} \sim 10^{-14} \mathrm{e\ cm}$$

- A non-zero EDM requires
  - P violation: the price to pay is $\approx 10^{-7}$, and
  - CP violation (from K-decays): the price to pay is $\approx 10^{-3}$

- In summary: $\boxed{|\boldsymbol{d_N}| \approx \mathbf{10^{-7}} \times \mathbf{10^{-3}} \times \boldsymbol{\mu_N} \approx \mathbf{10^{-24}\ e\ cm}}$

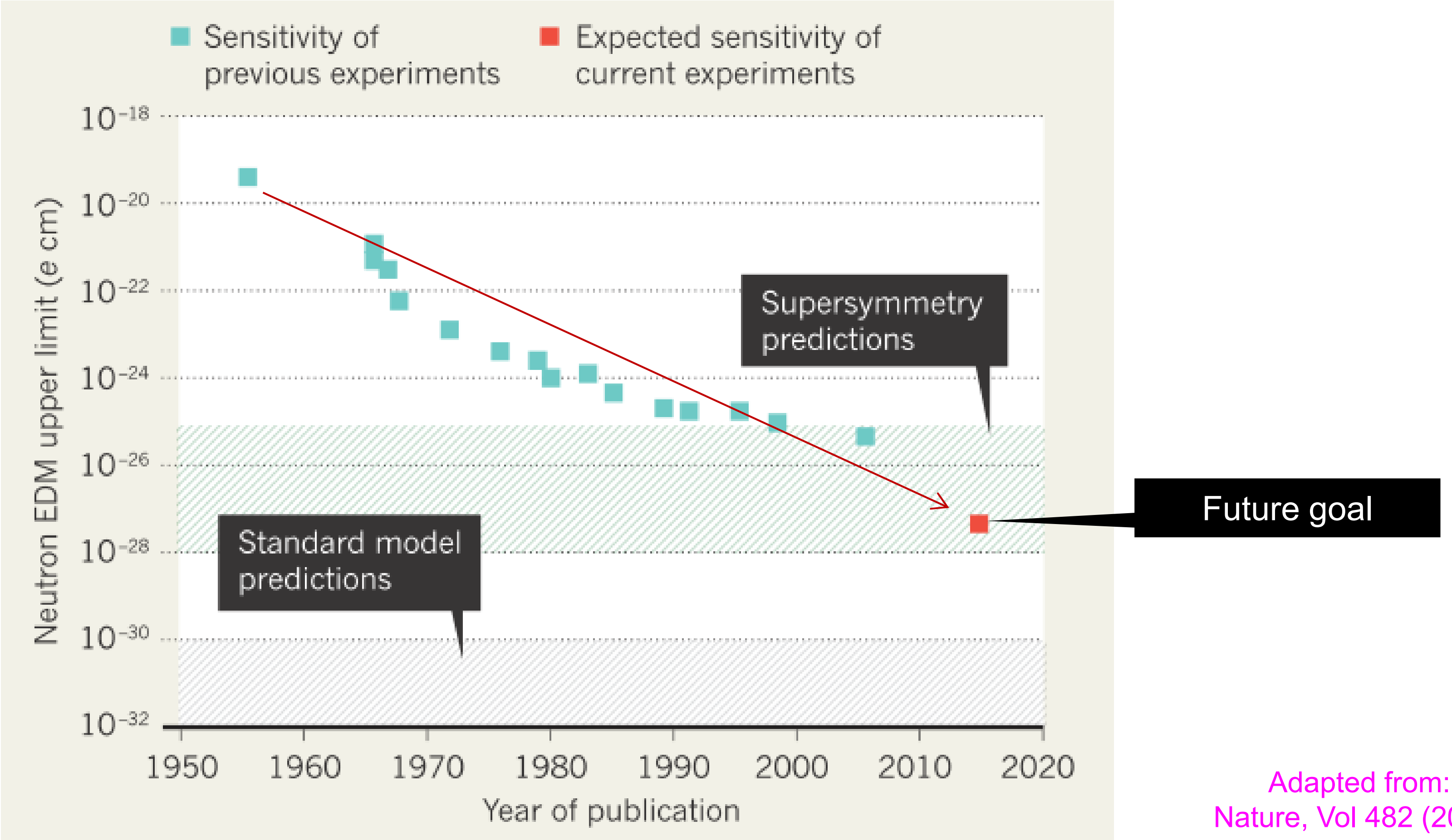
- In SM (without θ term): $\boxed{|\boldsymbol{d_N}^{\mathbf{SM}}| \approx \mathbf{10^{-7}} \times \mathbf{10^{-24}} \approx \mathbf{10^{-31}\ e\ cm}}$

⇒ Region to search for BSM physics $(\theta_{\mathrm{QCD}} = 0)$:

$$\mathbf{10^{-24} e\ cm} > |\boldsymbol{d_N}| > \mathbf{10^{-31}\ e\ cm}$$

EDMs: Precision Frontier

Example: Neutron (nEDM)

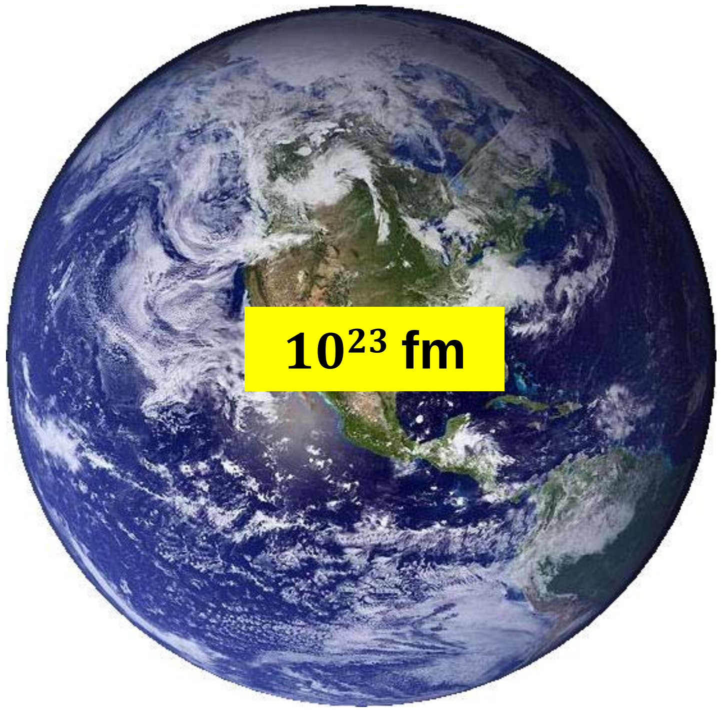


Adapted from:
Nature, Vol 482 (2012)

Search for Electric Dipole Moments (EDM) of fundamental particles

EDMs: **Precision Frontier**

Nucleon $\longrightarrow$ Earth

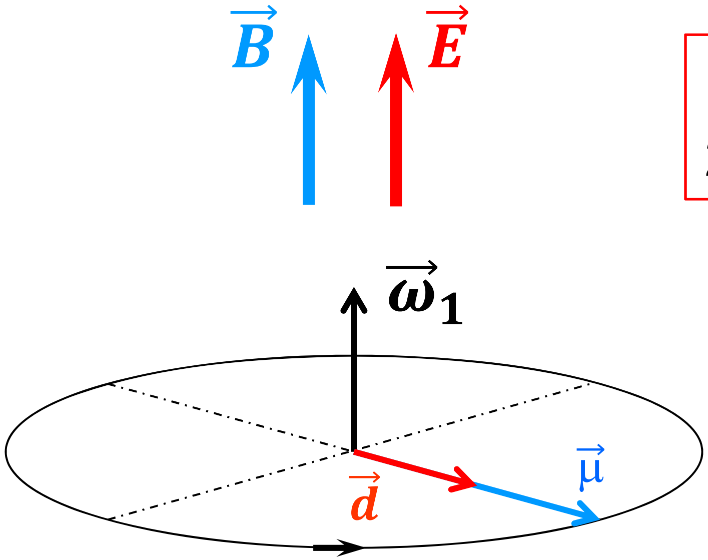


Present **upper limit nEDM** →
separation ≈ diameter of a thin hair ($\approx 10\ \mu\text{m}$)

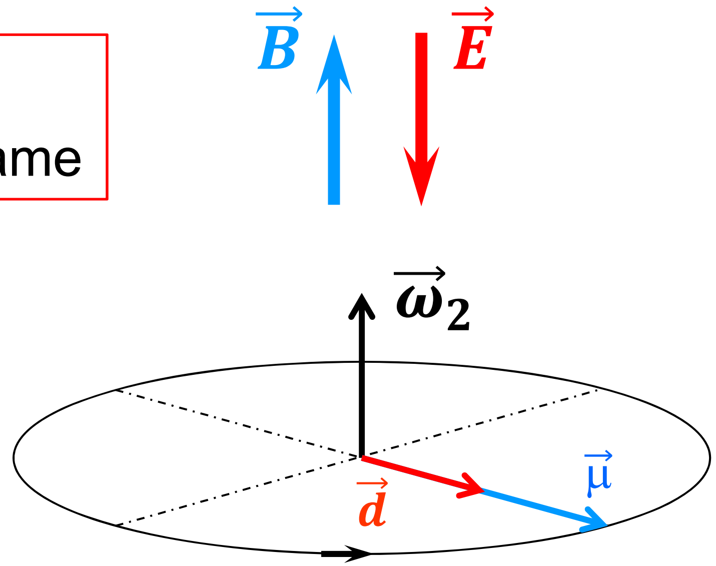
EDMs are tiny!

Measurement principle: Neutral particle EDM

Particle in ground state: $\boldsymbol{s} = \frac{1}{2}$



1. Reverse $\vec{E}$
2. Keep $\vec{B}$ the same



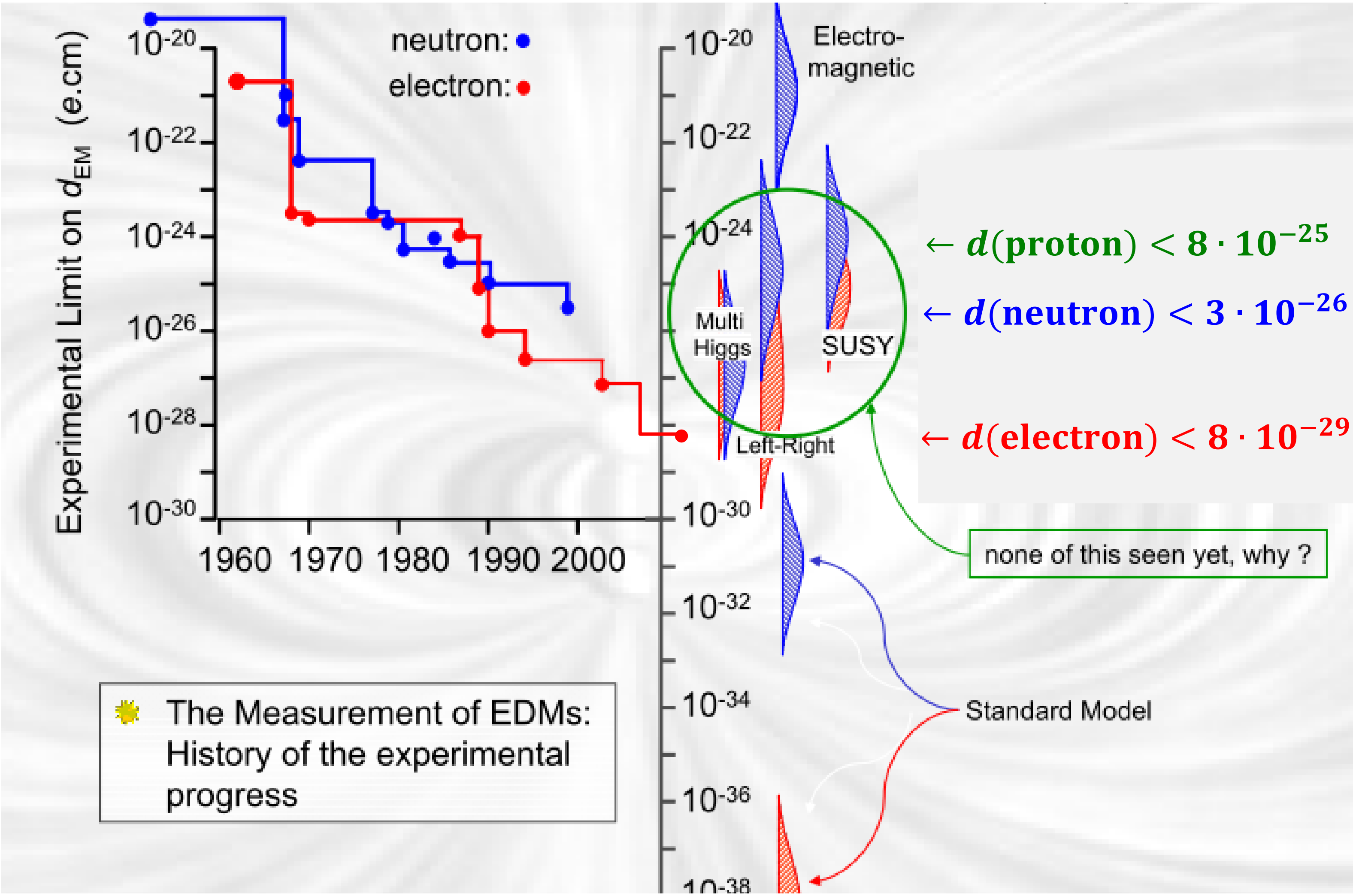
$$\omega_1 = \frac{2\mu B + 2dE}{h}$$

$$\boxed{\Rightarrow \omega_1 - \omega_2 = \frac{4dE}{h}}$$

$$\omega_2 = \frac{2\mu B - 2dE}{h}$$

One challenge: Shield external sources of B to levels $|B_{\text{ext}}| < 1\ \text{nT}$.

Physics Potential of EDMs



J.M. Pendlebury: „nEDM has killed more theories than any other single exp't"

Physics: Present limits of EDMs

EDM searches: Up to now only upper limits (in $e \cdot cm$)

Particle/Atom	Current EDM Limit	Future Goal
Electron	$< 8.7 \cdot 10^{-29}$	
Muon	$< 1.8 \cdot 10^{-19}$	
Neutron	$< 3 \cdot 10^{-26}$	$\sim 10^{-28}$
^{199}**Hg**	$< 3.1 \cdot 10^{-29}$	$\sim 10^{-29}$
^{129}**Xe**	$< 6 \cdot 10^{-27}$	$\sim 10^{-30} - 10^{-33}$
Proton	$< 7.9 \cdot 10^{-25}$	$\sim 10^{-29}$
Deuteron	?	$\sim 10^{-29}$

- No direct measurements of electron (ThO molecule) or proton ($^{199}\mathrm{Hg}$) EDMs
- No measurement at all of deuteron EDM

Large effort on worldwide scale to improve limits and to find EDMs

Physics: Ongoing/planned Searches

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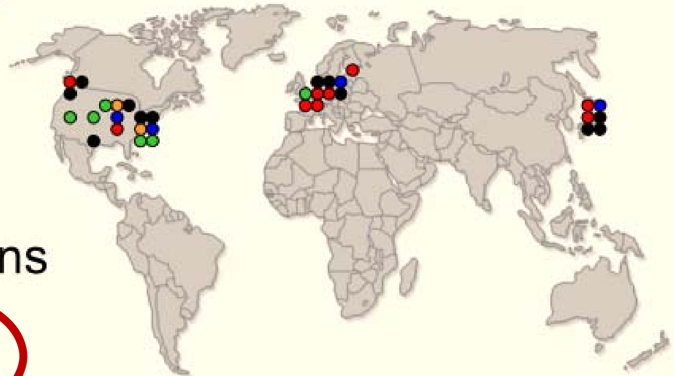
Rough estimate of numbers of researchers, in total ~500 (with some overlap)

- Neutrons ~200
  - @ILL
  - @ILL,@PNPI
  - @PSI
  - @FRM-2
  - @RCNP,@TRIUMF
  - @SNS
  - @J-PARC

- Molecules ~50
  - YbF@Imperial
  - PbO@Yale
  - ThO@Harvard
  - HfF+@JILA
  - WC@UMich
  - PbF@Oklahoma

- Atoms ~100
  - Hg@UWash
  - Xe@Princeton
  - Xe@TokyoTech
  - Xe@TUM
  - Xe@Mainz
  - Cs@Penn
  - Cs@Texas
  - Fr@RCNP/CYRIC
  - Rn@TRIUMF
  - Ra@ANL
  - Ra@KVI
  - Yb@Kyoto



- Ions-Muons ~200
  - @BNL
  - @FZJ
  - @FNAL
  - @JPARC

new

- Solids ~10
  - GGG@Indiana
  - ferroelectrics@Yale

P. Harris, K. Kirch … A large worldwide effort

Prospects of **charged particle EDMs:**

- No direct measurements of charged hadron EDMs
- Potentially higher sensitivity than neutrons
  - protons/deuterons are stable
  - more stored polarized protons/deuterons
  - larger electric fields
- Approach complimentary to neutron EDM
- EDM of a single particle not sufficient to identify CPV source
  - $d_d \stackrel{?}{=} d_p + d_n \Rightarrow$ access to θ_{QCD}

Charged particle EDM experiments potentially provide a higher sensitivity than, e.g., nEDM

Concepts for srEDM: Frozen spin Method

For transverse electric and magnetic fields in a ring, the ***anomalous*** spin precession is described by Thomas-BMT equation:

$$\vec{\Omega}_{\mathrm{MDM}} = \frac{q}{m}\left\{\cancel{G\vec{B}} - \cancel{\frac{\gamma G}{\gamma+1}\vec{\beta}(\vec{\beta}\cdot\vec{E})} - \left[G - \frac{1}{\gamma^2-1}\right]\frac{\vec{\beta}\times\vec{E}}{c}\right\} \qquad \left(G = \frac{g-2}{2}\right)$$

Magic condition: Spin along momentum vector

1. For any sign of G, in a combined electric and magnetic machine

$$E = \frac{GBc\beta\gamma^2}{1-G\beta^2\gamma^2} \approx GBc\beta\gamma^2,$$ where $E = E_{\mathrm{radial}}$ and $B = B_{\mathrm{vertical}}$

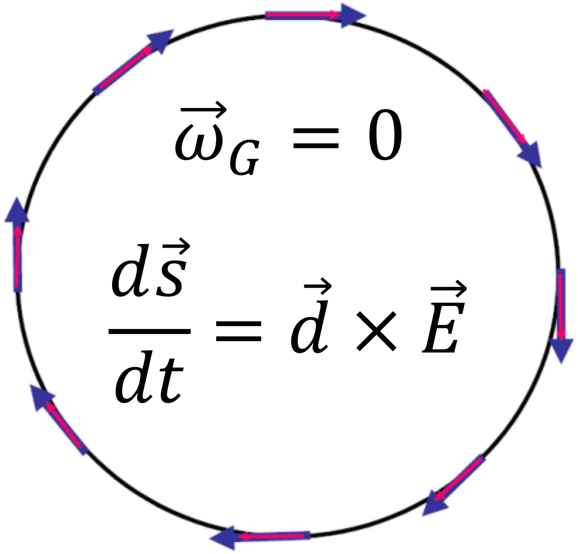
2. For $G > 0$ (protons) in an all electric ring

$$G - \left(\frac{m}{p}\right)^2 = 0 \Rightarrow p = \frac{m}{\sqrt{G}} = 700.74\ \mathrm{MeV/c} \quad \text{(magic)}$$

→ Magic rings to measure EDMs of **free** charge particles

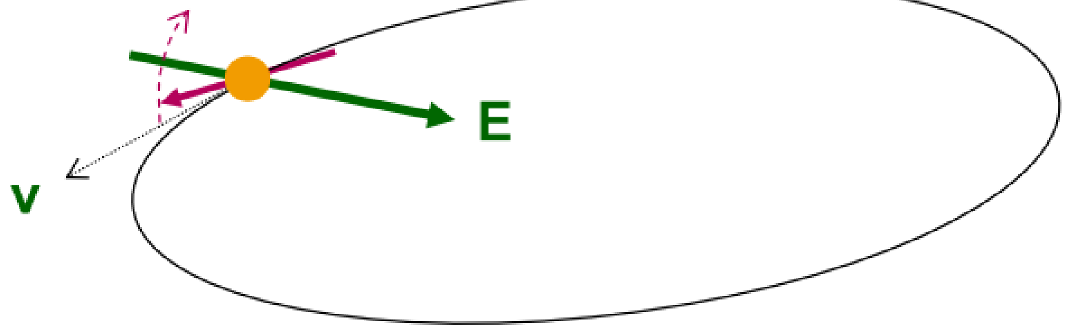
Concept: Rings for EDM searches

- **Place particles in a storage ring**
- **Align spin along** momentum („freeze“ horizontal spin precession)
- **Search for time development of vertical polarization**



$$\vec{\omega}_G = 0$$

$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$

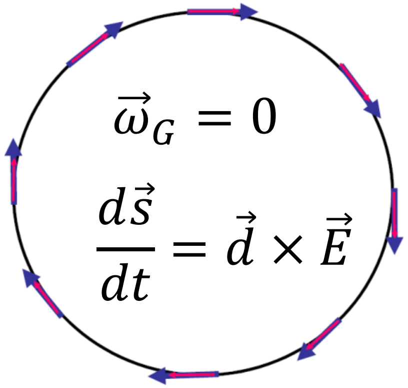


New Method to measure EDMs of charged particles:

- **Magic rings with spin frozen along momentum**
- **Polarization buildup $P_y(t) \sim d$**

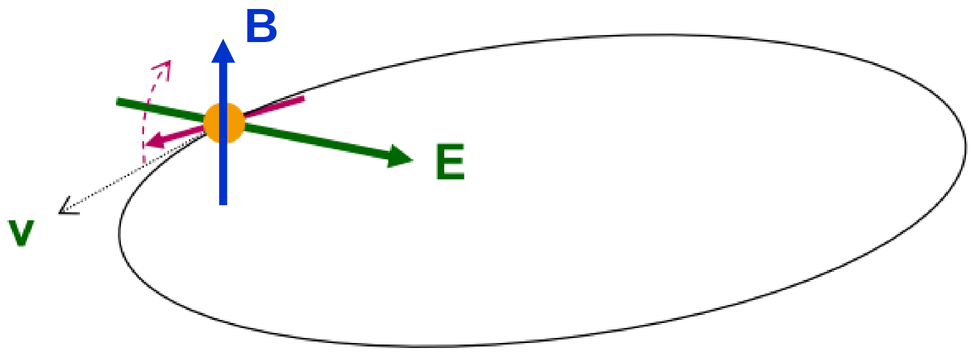
Concepts: *Magic* Storage ring

A *magic* storage ring for protons (electrostatic), deuterons, …



$$\vec{\omega}_G = 0$$

$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$



particle	p (MeV/c)	T (MeV)	E (MV/m)	B (T)
proton	701	232.8	16.789	0.000
deuteron	1000	249.9	−3.983	0.160
^{3}He	1285	280.0	17.158	−0.051

Possible to measure p, d, ^{3}He using **one** machine with $r \sim 25$ m

Concept: Experimental requirements

- High precision, primarily electric storage ring
  - alignment, stability, field homogeneity, and shielding from perturbing magnetic fields
- High beam intensity ($N = 4 \cdot 10^{10}$ per fill)
- Stored polarized hadrons ($P = 0.8$)
- Large electric fields ($E = 10\ \mathrm{MV/m}$)
- Long spin coherence time ($\tau_{\mathrm{SCT}} = 1000\ \mathrm{s}$)
- Efficient polarimetry (analyzing power $A_y \approx 0.6, f = 0.005$)

$$\boldsymbol{\sigma_{\mathrm{stat}} \approx \frac{1}{\sqrt{N \cdot f} \cdot \tau \cdot P \cdot A_y \cdot E} \Rightarrow \sigma_{\mathrm{stat}}(1\ \mathrm{year}) = 10^{-29}\ \mathrm{e \cdot cm}}$$

Goal: provide σ_{syst} to the same level

Concept: Systematics

Magnetic fields:

- Radial field B_r mimics EDM effect when $\mu \times B_r \approx d \times E_r$
- With $d = 10^{-29}\ \mathrm{e \cdot cm}$ in a field of $E = 10\ \mathrm{MV/m}$,

$$B_r = \frac{dE_r}{\mu_n} = \frac{10^{-31} \cdot 10^{7}\,\mathrm{eV}}{3.152 \cdot 10^{-8}\ \mathrm{eV/T}} = 3.1 \cdot 10^{-17}\ \mathrm{T}$$

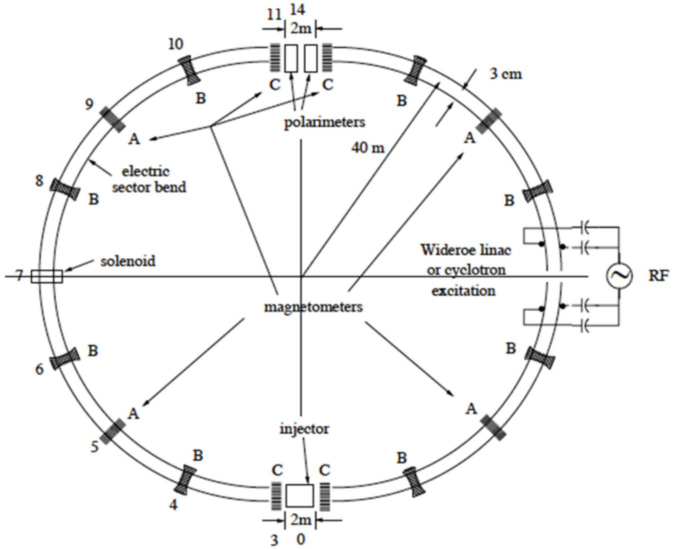
- **Solution:** Use two beams *simultanously*, clockwise (CW) and counter-clockwise (CCW), the vertical separation of the beam orbits is sensitive to B_r.

Use CW and CCW beams to tackle systematics

Concepts: Beat the systematics

2 beams simultaneously rotating in an all electric ring (CW, CCW)

	CW		CCW	
Polarization (P_z)	$+$	$-$	$+$	$-$
EDM $(\vec{d} \times \vec{E})$	$-$	$+$	$+$	$-$
Sokolov-Ternov	$-$	$-$	$+$	$+$
Gravitation	$-$	$+$	$-$	$+$



CW & CCW beams cancel many systematic effects

Concept: Systematic Orbit splitting (Dave Kawall)

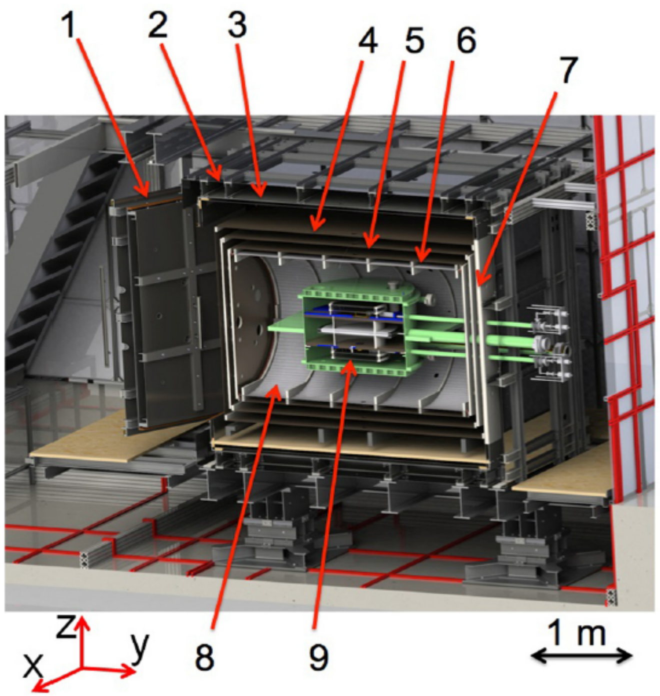
- Splitting of beam orbits: $\delta y = \pm \frac{\beta c R_0 B_r}{E_r {Q_y}^2} = \pm 1 \cdot 10^{-12}\ \mathrm{m}$
- $Q_y \approx 0.1$ denotes the vertical betatron tune
- Modulate $Q_y = {Q_y}^0 [1 - m \cos(\omega_m t)]$, with $m \approx 0.1$
- Splitting corresponds to $B \approx 0.4 \cdot 10^{-3}\ \mathrm{fT}$
- In one year of measurement: 10^4 fills of $1000\ s$ each
  $\Rightarrow\ \sigma_B = 0.4 \cdot 10^{-1} \mathrm{fT}$ per fill

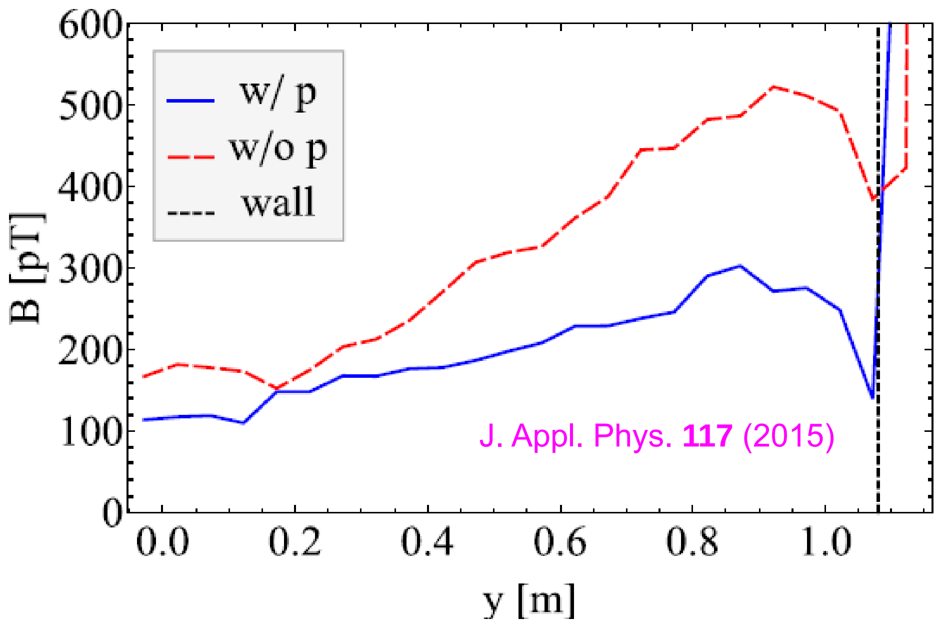
Required sensitivity $\approx 1.25\ \mathrm{fT}/\sqrt{\mathrm{Hz}}$, achievable only with state-of-the-art SQUID magnetometers.

Recent Progress: Magnetic shielding

Next generation nEDM experiment under development at TUM (FRM II):

- **Goal:** Improve present nEDM limit by factor 100.
- Experiment shall use multi-layer shield.
- Applied magnetic field: $\mathrm{B} \approx 1\text{–}2.5\ \mu\mathrm{T}$.



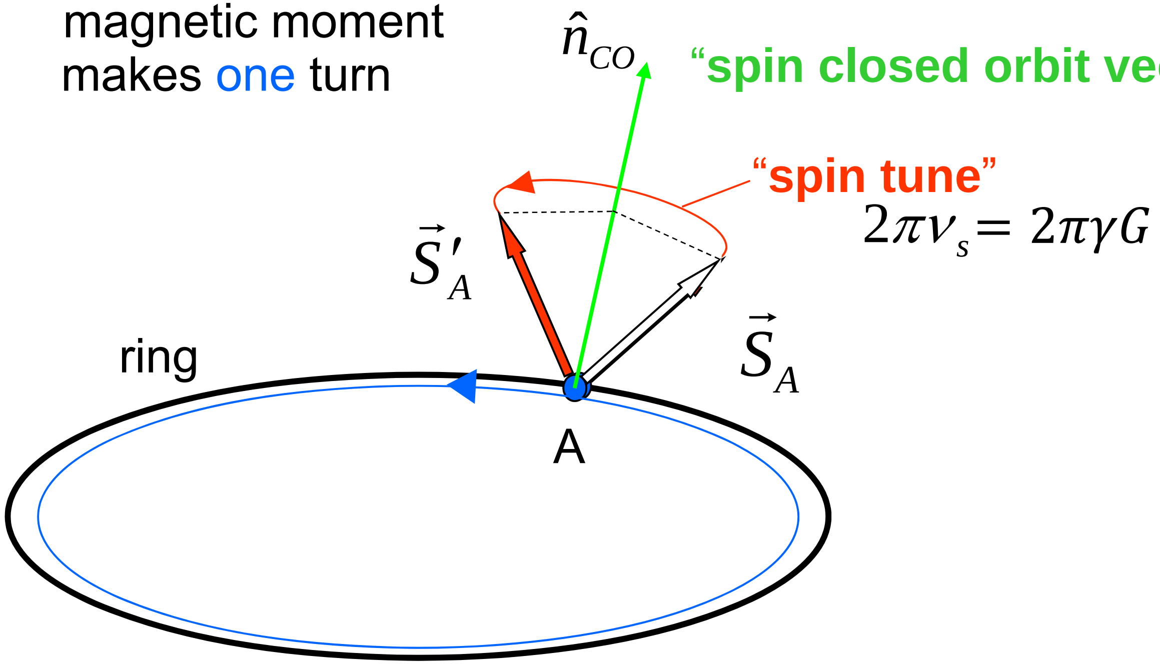


At mHz frequencies, damping of $|B_{\mathrm{ext}}| \approx 1 \cdot 10^6$ achieved

Insert: Spin closed orbit and spin tune

Spin closed orbit

one particle with magnetic moment makes one turn

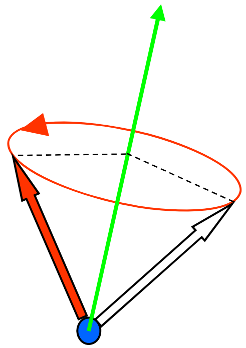


stable polarization
if $\vec{S} \parallel \hat{n}_{CO}$

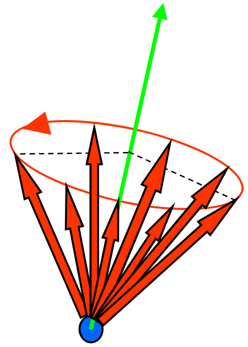
The number of spin precessions per turn is called spin tune $\boldsymbol{\nu_s}$

Challenge: Spin coherence time (SCT)

We usually don‘t worry about coherence of spins along $\hat{n}_{co}$



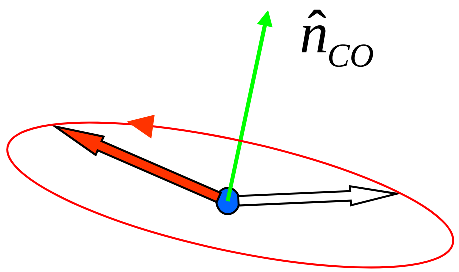
At injection all
spin vectors aligned (coherent)



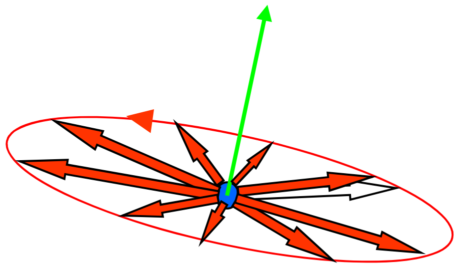
After some time, spin vectors get out of
phase and fully populate the cone

Polarization along
$\hat{n}_{co}$ not affected!

Situation very different, when you deal with $\vec{S} \perp \hat{n}_{co}$ machines with frozen spin.



At injection all spin vectors aligned



Later, spin vectors are out of
phase in the horizontal plane

Longitudinal polarization
vanishes!

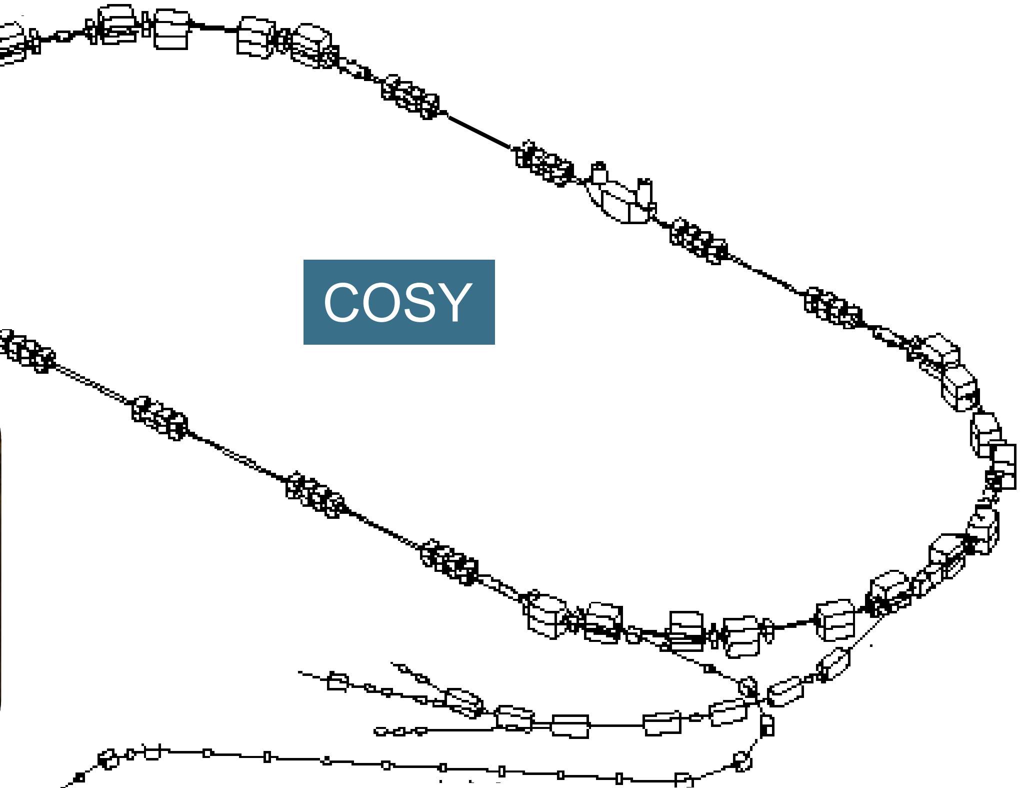
In a machine with frozen spins the buildup time
to observe a polarization $P_y(t)(\approx d)$ is limited by τ_{SCT}.

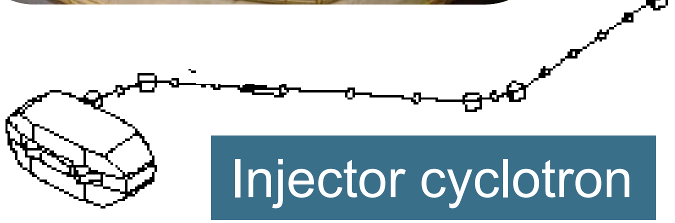
EDM at COSY: COoler SYnchrotron

Cooler and storage ring for (polarized) protons and deuterons

$p = 0.3 - 3.7\ \mathrm{GeV}/c$

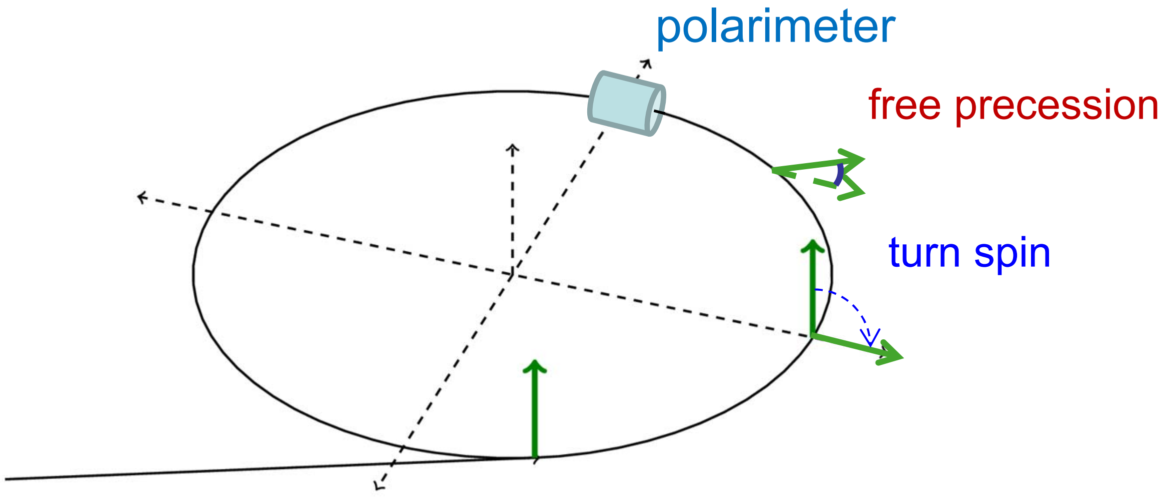
Phase space cooled internal & extracted beams





…an ideal starting point for EDM search

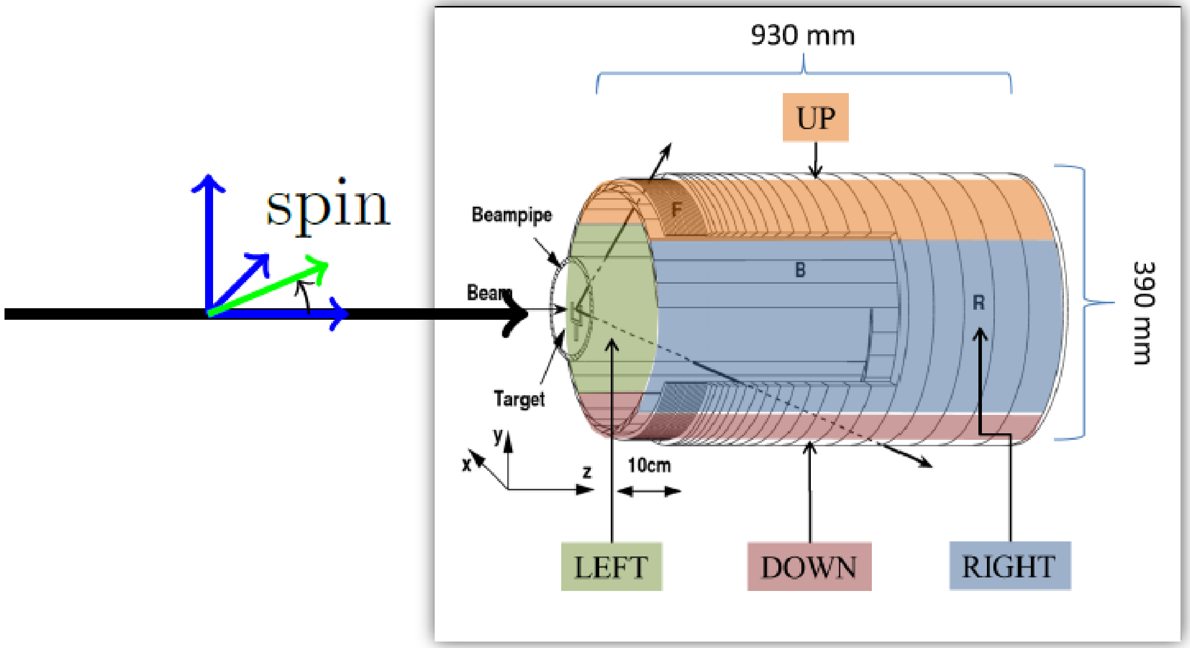
Spin coherence time: Experimental investigation



1. Vertically polarized deuterons stored in COSY at $p \approx 1\,\frac{\mathrm{GeV}}{\mathrm{c}}$.
2. The polarization is flipped into horizontal plane with RF solenoid (takes $\approx 200\ \mathrm{ms}$).
3. Beam slowly extracted on Carbon target with ramped bump or by heating the beam.
4. Horizontal (in-plane) polarization determined from Up-Do asymmetry in the detector.

Need to keep track of event time and revolution time from turn to turn

Polarimeter: Experimental investigation of SCT

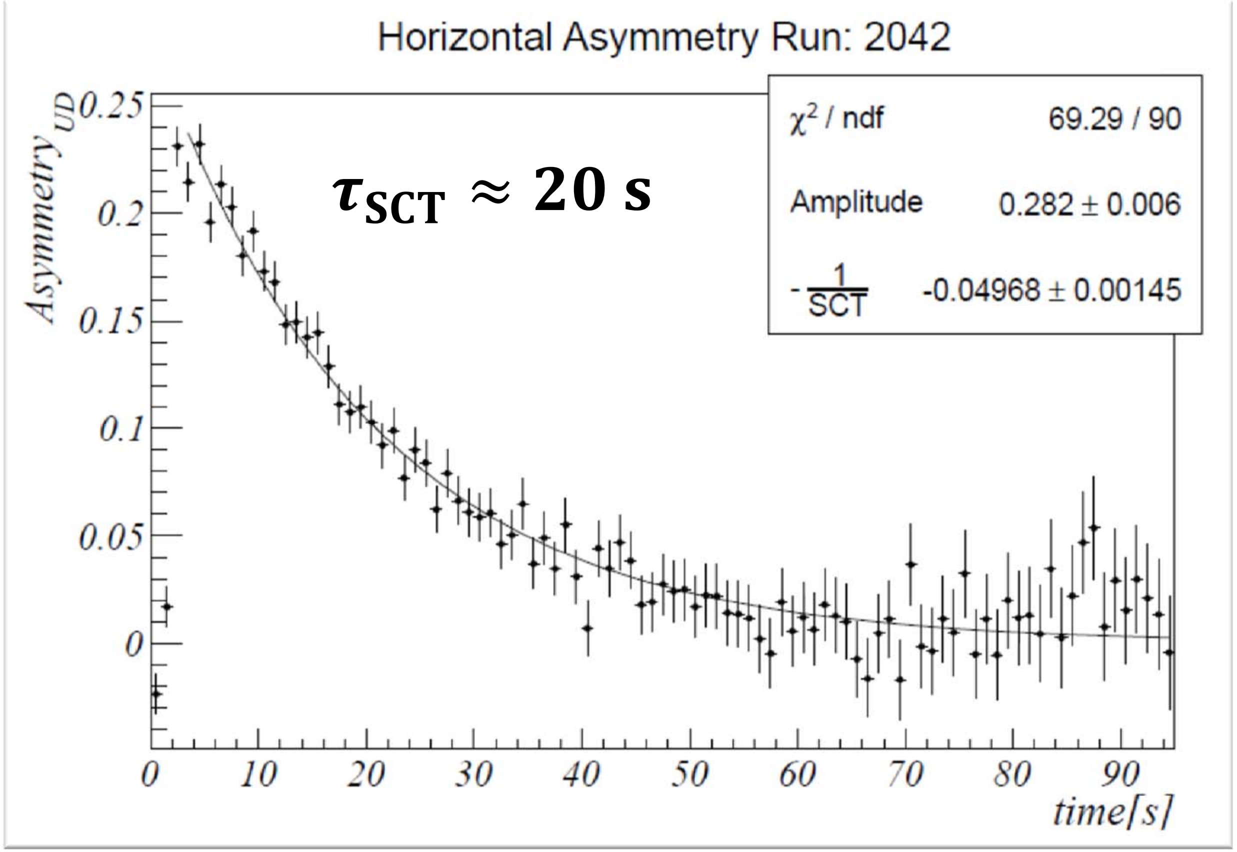


Detect deuterons from dC scattering:

- Deuterons at $p \approx 1\ \mathrm{GeV}/c$ ($\gamma = 1.13$), $f_{\mathrm{rev}} \approx 781\ \mathrm{kHz}$
- $G_d = -0.143,\ \nu_s \approx \gamma \cdot G_d = -0.161$
- $N_{U,D} \propto 1 \pm \frac{3}{2} p \cdot A_y \cdot \sin(\omega_s t)\,, \omega_s = 2\pi f_{\mathrm{rev}} \nu_s \approx 120\ \mathrm{kHz}$

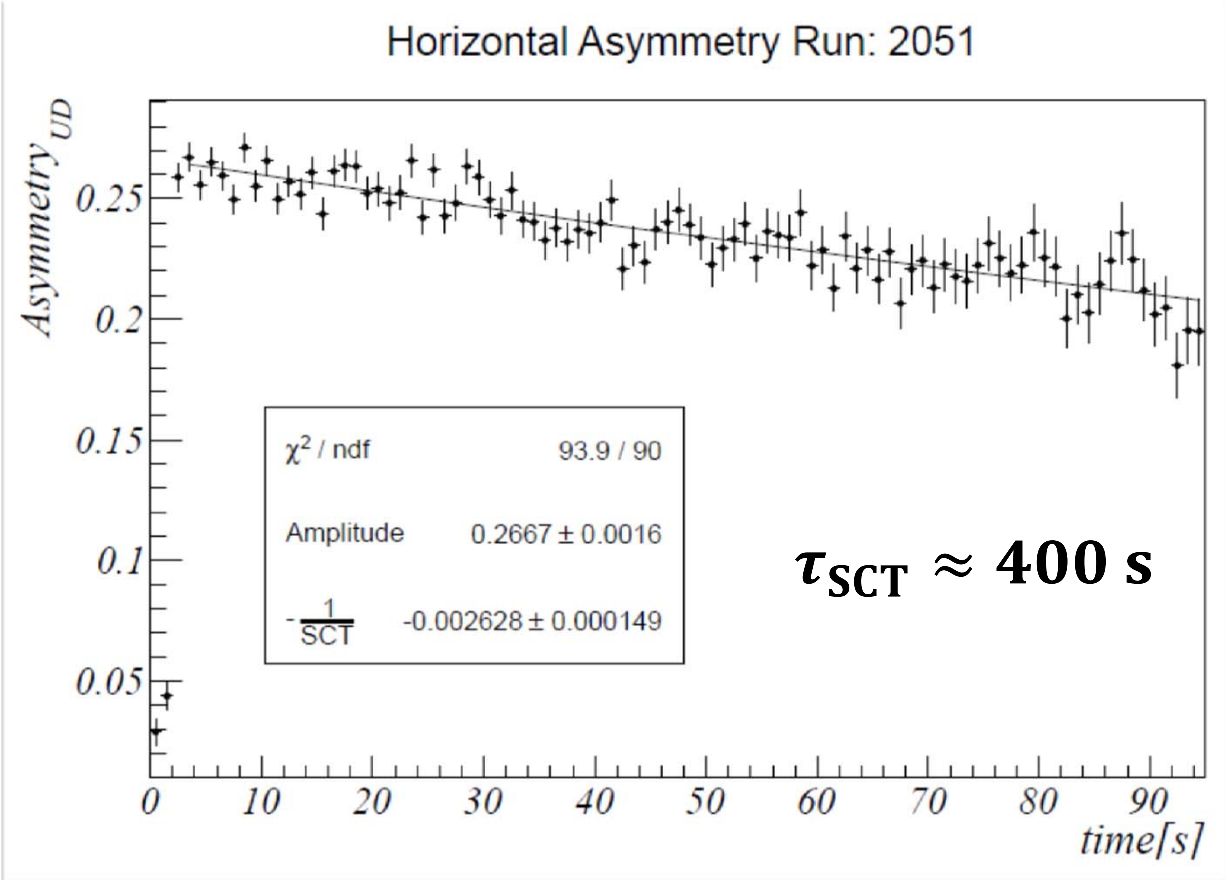
Polarimeter: Determination of SCT

Observed experimental decay of asymmetry $\varepsilon_{UD} = \frac{N_D - N_U}{N_D + N_U}$ as function of time, $\varepsilon_{UD}(t) \approx P(t)$.

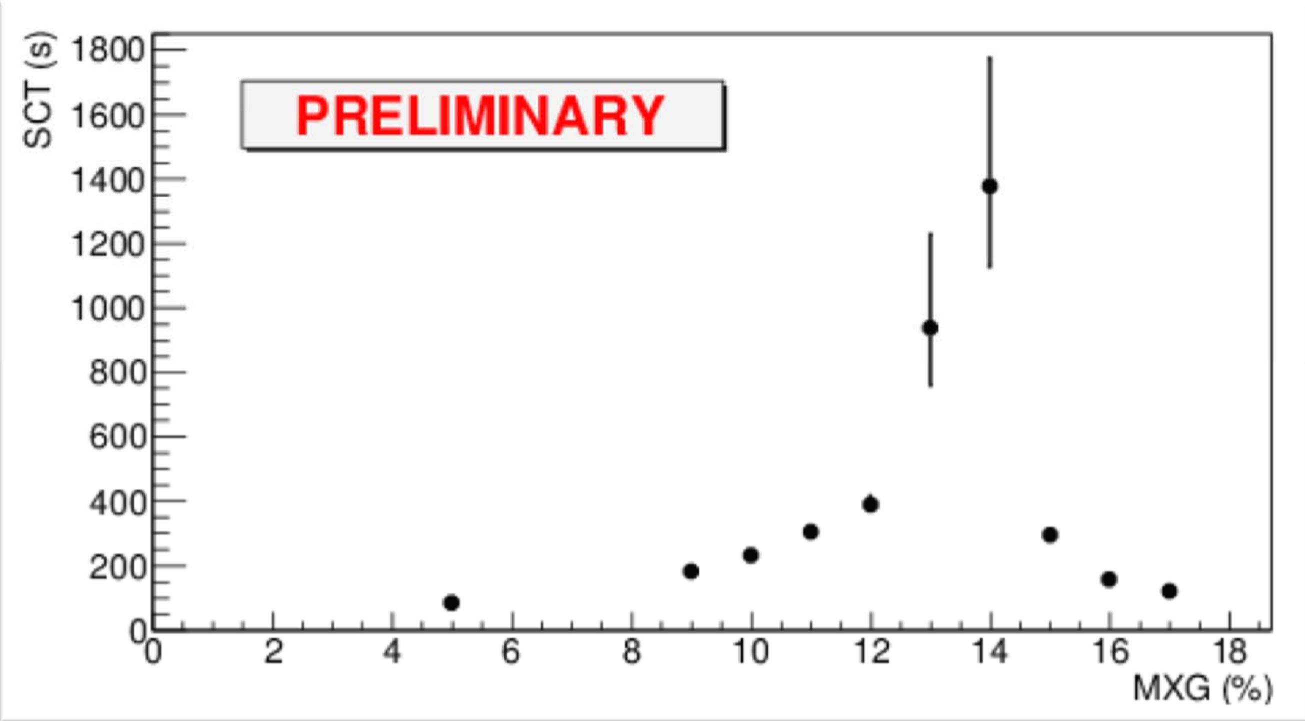


Polarimeter: Optimization of SCT

Using sextupole magnets in the machine, higher order effects can be corrected, and the SCT is substantially increased



SCT: Optimization



Measurements of the horizontal polarization lifetime as a function of the strength of the MXG sextupole family with MXS set to 10% and MXL set to -1.45% of power supply full scale.

Excellent progress towards the SCT goal for pEDM: $\tau_{\mathrm{SCT}} \sim 1000$ s

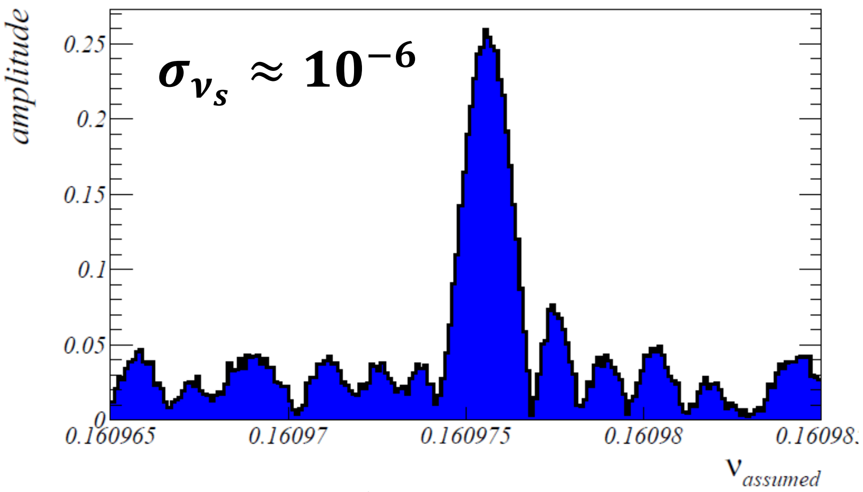
Spin tune ν_s: How to measure it?

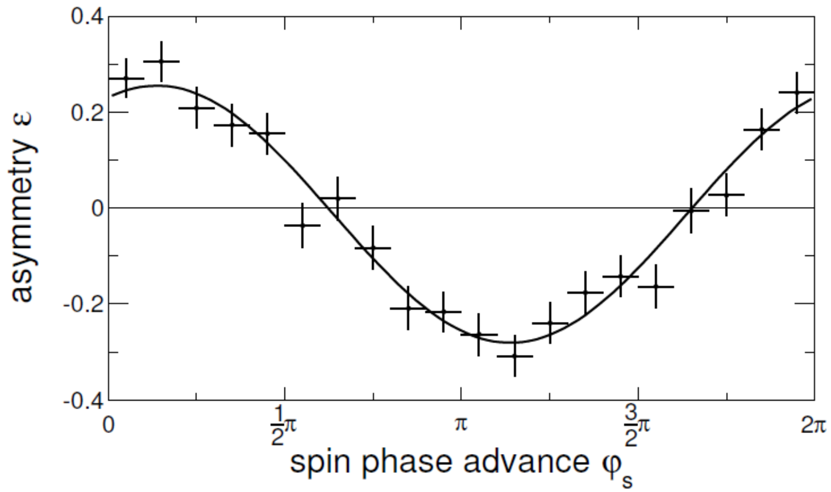
$\nu_s \equiv$ Number of spin precessions revolution, a priori not known ($\approx \gamma G$)

- Detector rate is $\approx 5\ \mathrm{kHz}$, $f_{\mathrm{rev}} = 781\ \mathrm{kHz}$ → one hit in detector per 25 beam revolutions

Scan ν_s in an interval around γG and find maximum of asymmetry ε_{UD}

COSY rf → T → beam revolutions: counting turn number *n*



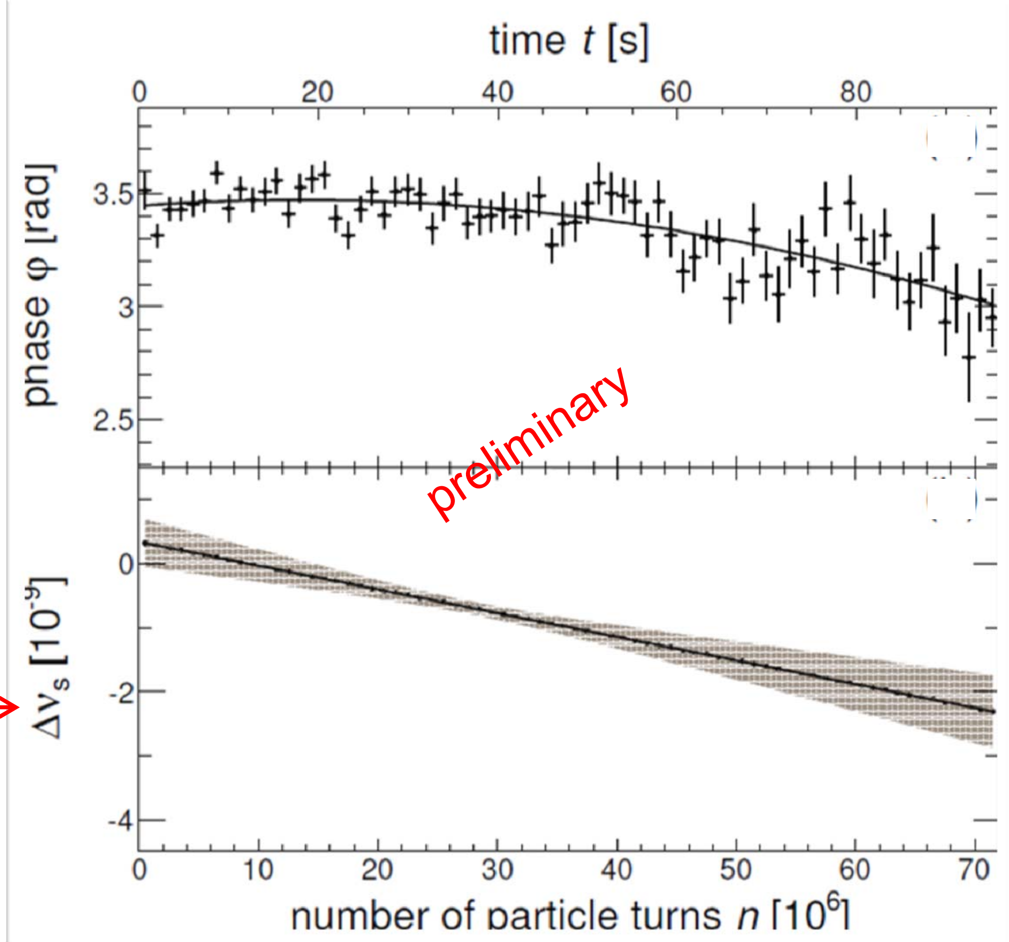


Solution: Map all events into one spin oscillation period

Spin tune: Determination of ν_s

Monitor phase of asymmetry with fixed ν_s during 100 s cycle

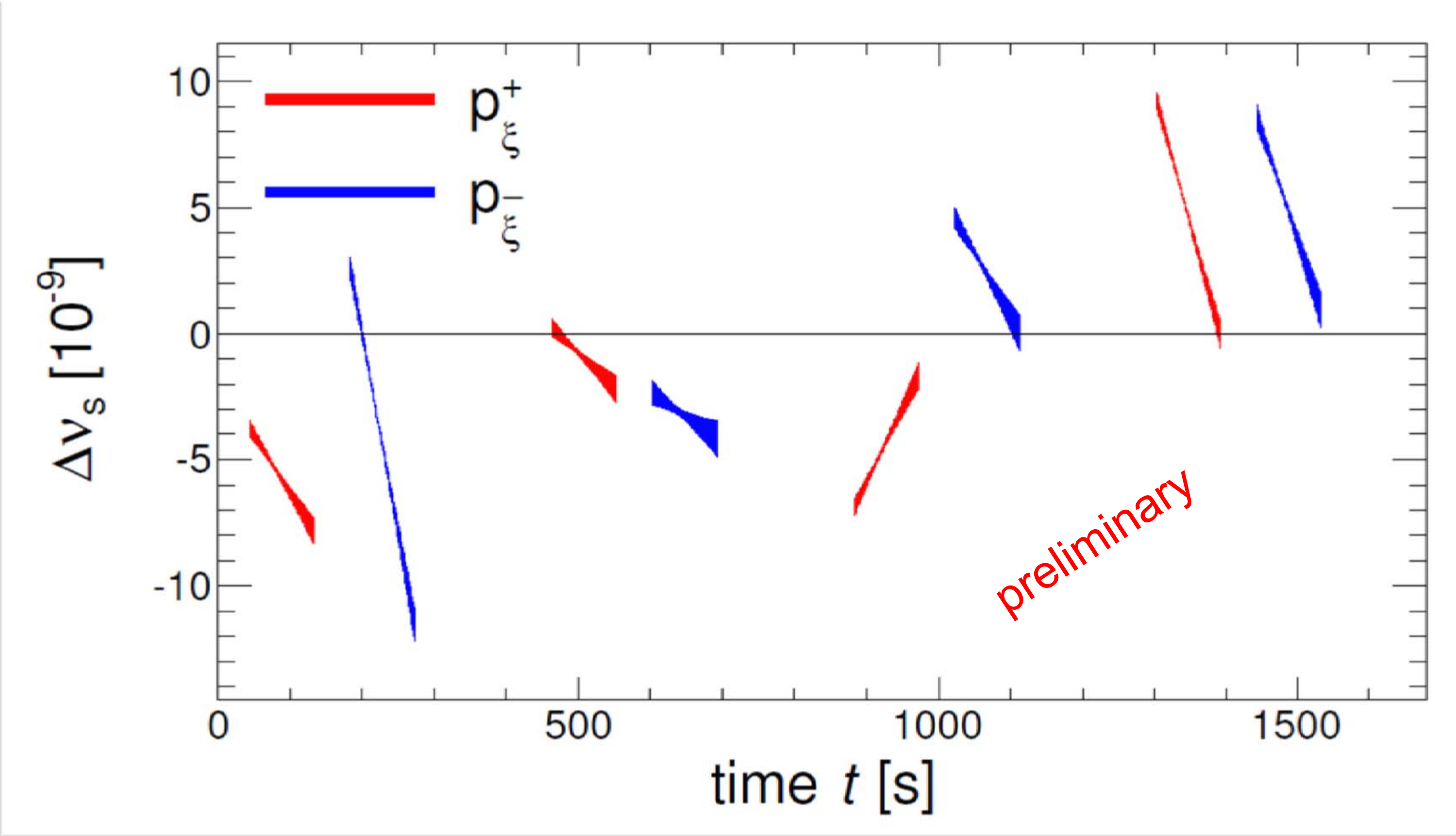
$$\nu_s(n) = \nu_s^{\text{fix}} + \frac{1}{2\pi}\frac{\mathrm{d}\tilde{\varphi}(n)}{\mathrm{d}n}$$
$$= \nu_s^{\text{fix}} + \Delta\nu_s(n)$$



Spin tune ν_s determined to $\approx 10^{-8}$ in 2 s time interval, and in a $100\ s$ cycle at $t \approx 40\ s$ to $\approx 10^{-10}$ (see arXiv:1504.00635, 2015)

Precision tool for accel. physics: Spin tune

Observed behavior of subsequent cycles



- Tool to optimze long term stability of a machine
- Develop feedback systems to minimize variations
- Phase-locking the spin precession to RF devices possible

Idea for proof-of-principle srEDM experiment

Use an RF technique:

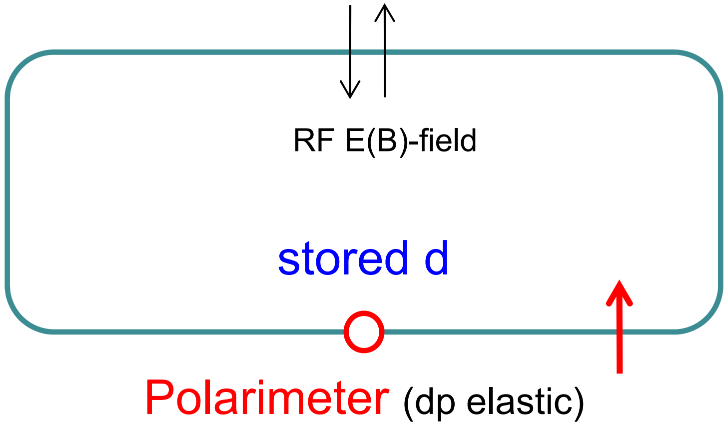
- **RF device operates on some harmonic of the spin precession frequency**
- **accumulate EDM signal with time**

Use COSY for a first direct p and d EDM measurement

First direct dEDM measurement : RF Wien filter

Avoids coherent betatron oscillations of beam.
Radial RF-E and vertical RF-B fields to observe spin rotation due to EDM.

$\boldsymbol{E}^* = \mathbf{0} \Rightarrow \boldsymbol{E}_R = -\beta \times \boldsymbol{B}_y$ **„Magic RF Wien Filter“** no Lorentz force
→ **Indirect** EDM effect



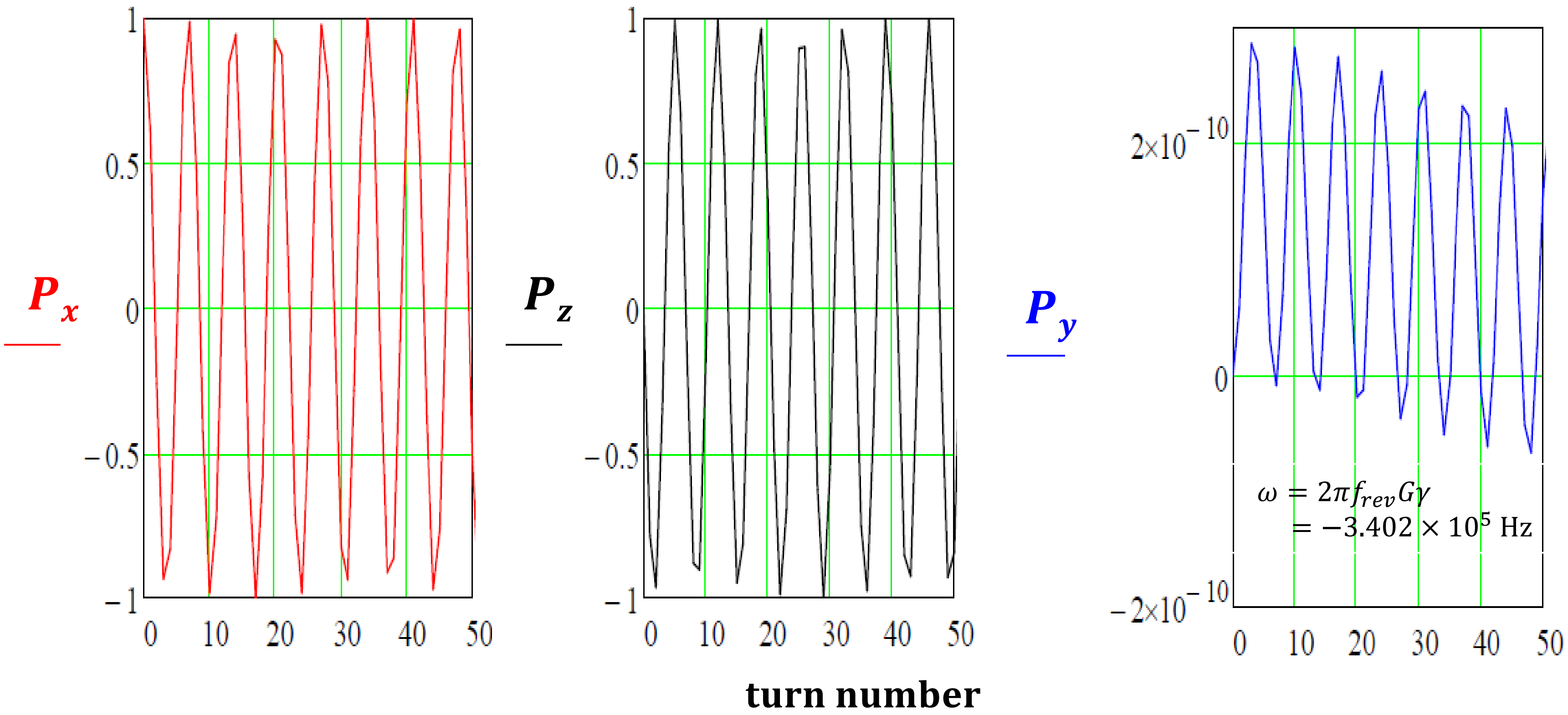
In-plane polarization

Observable:
Accumulation of vertical polarization during spin coherence time

Statistical sensitivity for d_d in the range 10^{-23} to 10^{-24} e·cm range
- Alignment and field stability of ring magnets
- Imperfection of RF-E(B) flipper

First direct EDM measurement: Deuterons

Parameters:	beam energy	$T_d = 50$ MeV	$L_{\mathrm{RF}} = 1$ m
	assumed EDM	$d_d = 10^{-24}$ e·cm	
	E-field	30 kV/cm	



EDM effect accumulates in P_y (see Phys. Rev. ST AB 16, 114001 (2013))

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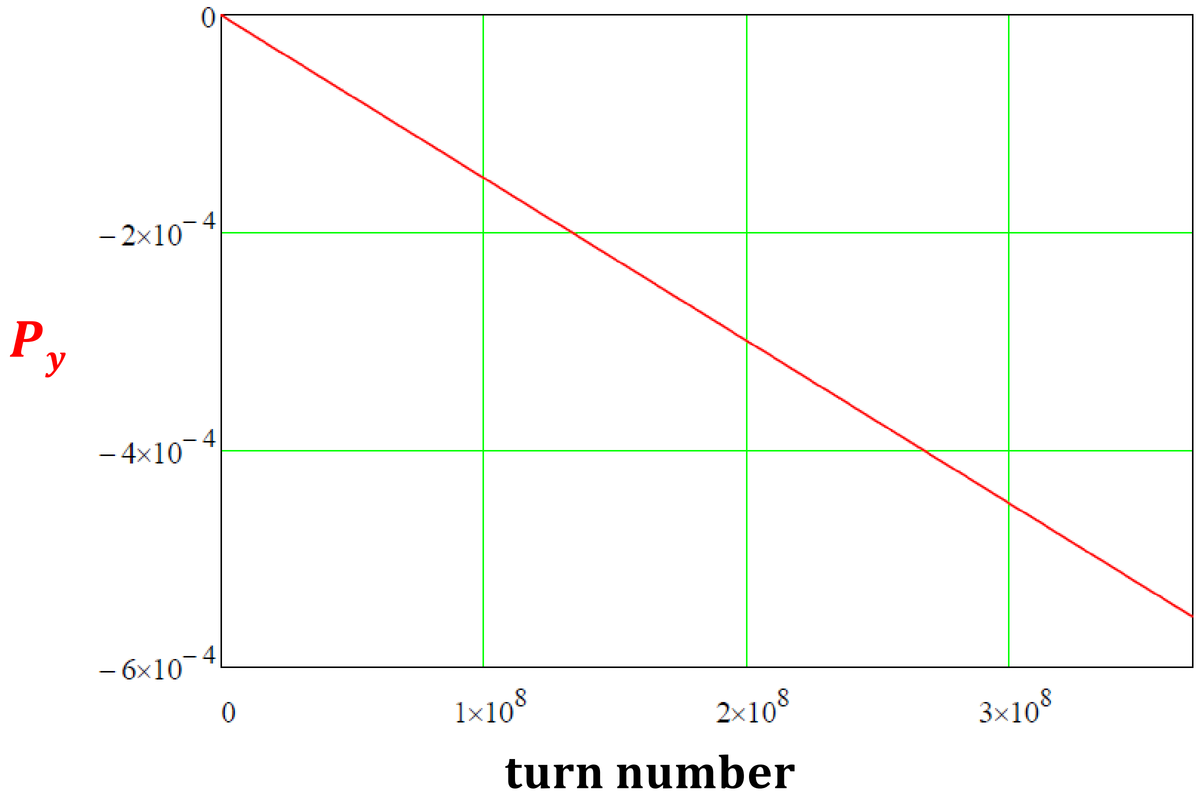
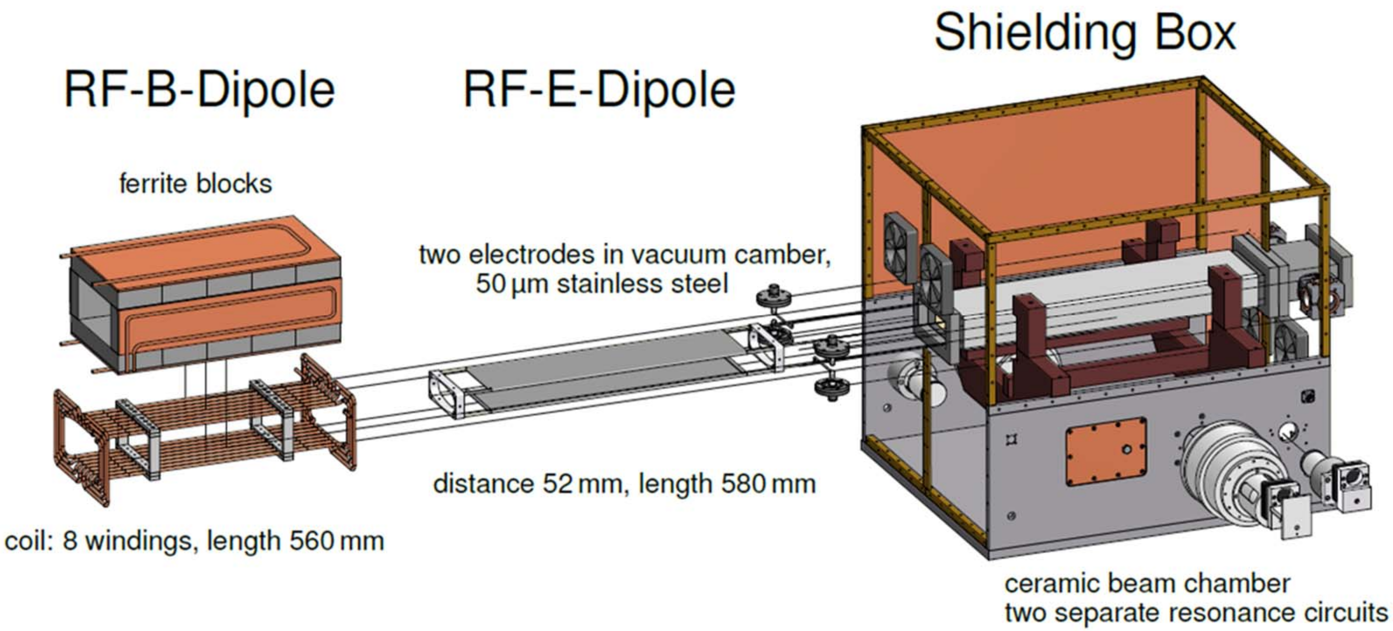
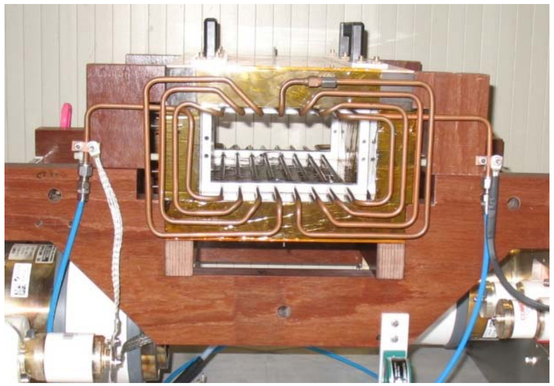
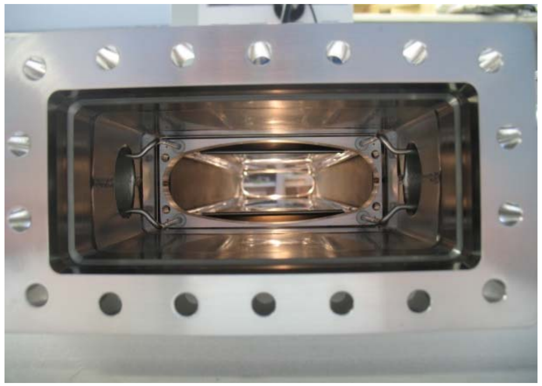


Linear extrapolation of P_y for a time period of $\tau_{sc} = 1000$ s ($= 3.7\cdot10^8$ turns) yields a sizeable $P_y \sim 10^{-3}$.

RF $\mathbf{E} \times \mathbf{B}$ Wien Filter: Prototype







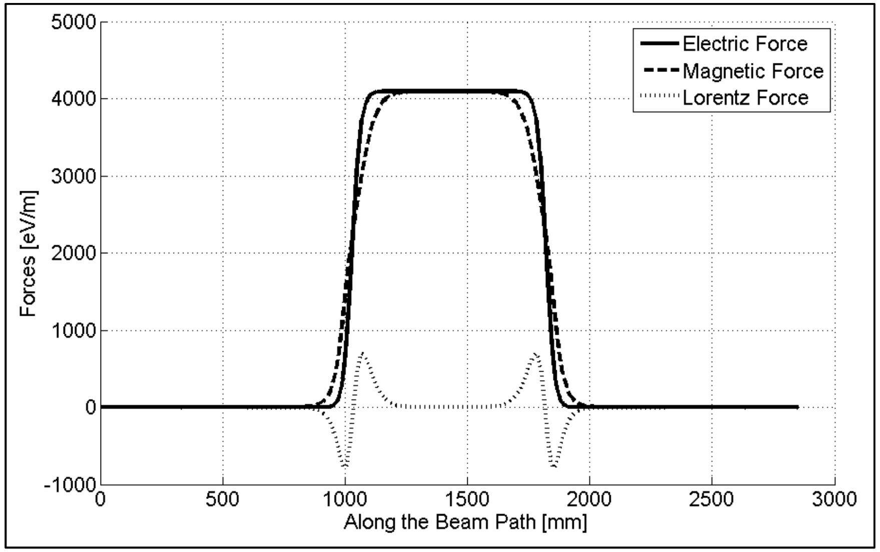
Commissioned prototype just performs like an RF solenoid

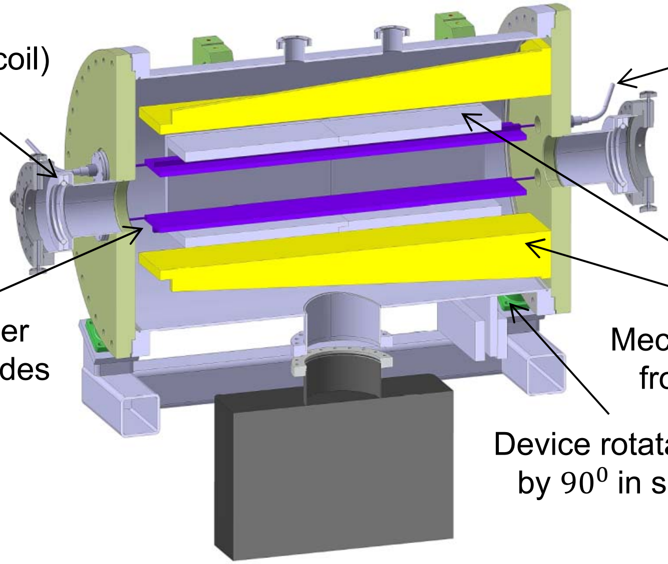
RF $\mathbf{E} \times \mathbf{B}$ Wien filter: Strip line design

Strip line design provides $\vec{E} \times \vec{B}$

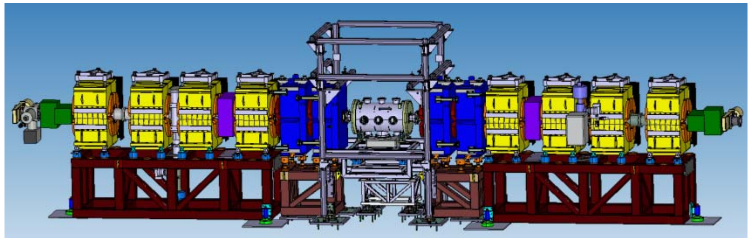
$$\int_{-L}^{L} B_y dz = 0.02371 \text{ Tmm}$$

$$F_L = \frac{1}{2L}\int_{-L}^{L} F_L dz = 1.8 \cdot 10^{-4} \ \frac{\text{eV}}{\text{m}}$$





Device will be installed in PAX low-β section



Strip-line RF E×B Wien filter available end of 2015.

Systematic study: Machine imperfections using two straight section solenoids

Systematic effects from machine imperfections limit the achievable precision in an EDM experiment using an RF $\mathrm{E} \times \mathrm{B}$ Wien filter.

Idea: Exploit precise determination of spin tune $\left(\frac{\Delta\nu_s}{\nu_s} \approx 10^{-10}\text{ in a cycle}\right)$ to map out the magnetic imperfections of machine.

COSY provides two solenoids in opposite straight sections:

1. one of the compensation solenoids of the 70 kV cooler: $\int \boldsymbol{B_z dz} \approx \mathbf{0.15\ Tm}$,
2. The main solenoid of the 2 MV cooler: $\int \boldsymbol{B_z dz} \approx \mathbf{0.54\ Tm}$.

Both devices available dynamically in the cycle, *i.e.*, their strength can be adjusted on flat top.

Systematic study: Thomas-BMT eq. $(d \neq 0)$ in magnetic machine

Goal: explore dynamics and systematic limitations of EDM searches in magnetic ring

$$\boxed{\frac{d\vec{s}}{dt} = \vec{s} \times \left(\vec{\Omega}_{\mathrm{MDM}} + \vec{\Omega}_{\mathrm{EDM}}\right)}$$

$$\vec{\Omega}_{\mathrm{MDM}} = \frac{q}{m}\left\{G \cdot \vec{B} - \frac{\gamma G}{\gamma + 1}\vec{\beta}\left(\vec{\beta} \cdot \vec{B}\right) - \left[G - \frac{1}{\gamma^2 - 1}\right]\frac{\vec{\beta} \times \vec{E}}{c}\right\}$$

$$\vec{\mu} = g\frac{q\hbar}{2m}\vec{s} = (G+1)\frac{q\hbar}{m}\vec{s}$$

$$\vec{d} = \frac{\eta q \hbar}{2m}\vec{s}$$

$$\vec{\Omega}_{\mathrm{EDM}} = \frac{\eta q}{2mc}\left\{\vec{E} - \frac{\gamma}{\gamma + 1}\vec{\beta}\left(\vec{\beta} \cdot \vec{E}\right) + c\vec{\beta} \times \vec{B}\right\}$$

BMT for magnetic machine with $d \neq 0$:

$$\boxed{\frac{d\vec{s}}{dt} = \frac{q}{m}\left\{G \cdot \vec{B} + \frac{\eta}{2}\left(\vec{\beta} \times \vec{B}\right)\right\}}$$

Interaction of EDM with motional E-field $(\vec{\beta} \times \vec{B})$ tilts stable spin axis:

$$\vec{n}_{co} = \vec{e}_x \sin\xi + \vec{e}_y \cos\xi \qquad \tan\xi = \frac{\eta}{2G}\beta \qquad \eta = 2d\frac{m}{q}$$

Misalignment of magnetic elements produces in-plane imperfection magnetic fields:

$$\boxed{\vec{n}_{co} = \vec{e}_x c_1 + \vec{e}_y c_2 + \vec{e}_z c_3}$$

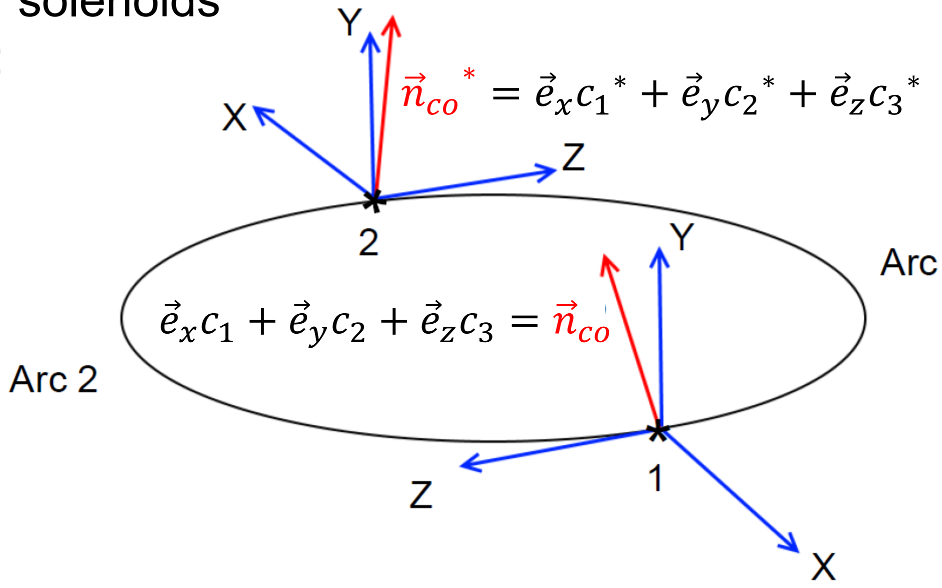
Non-vanishing c_1 and c_3 generate background to the EDM-signal of an ideal imperfection-free machine ($c_1 = \sin\xi$, $c_2 = \cos\xi$ and $c_3 = 0$).

The challenge is to control this background:
An accuracy $\Delta c_{1,3} \approx 10^{-6}\ \mathrm{rad}$ amounts to a sensitivity $d = 10^{-20}\ \mathrm{e \cdot cm}$.

Systematic study: Imperfection measurement

Probing the in-plane imperfection fields by introducing artificial imperfections and looking for the spin tune response

Use the compensation and e-cooler solenoids in straight sections (points 1 and 2): spin kicks χ_1 and χ_2.

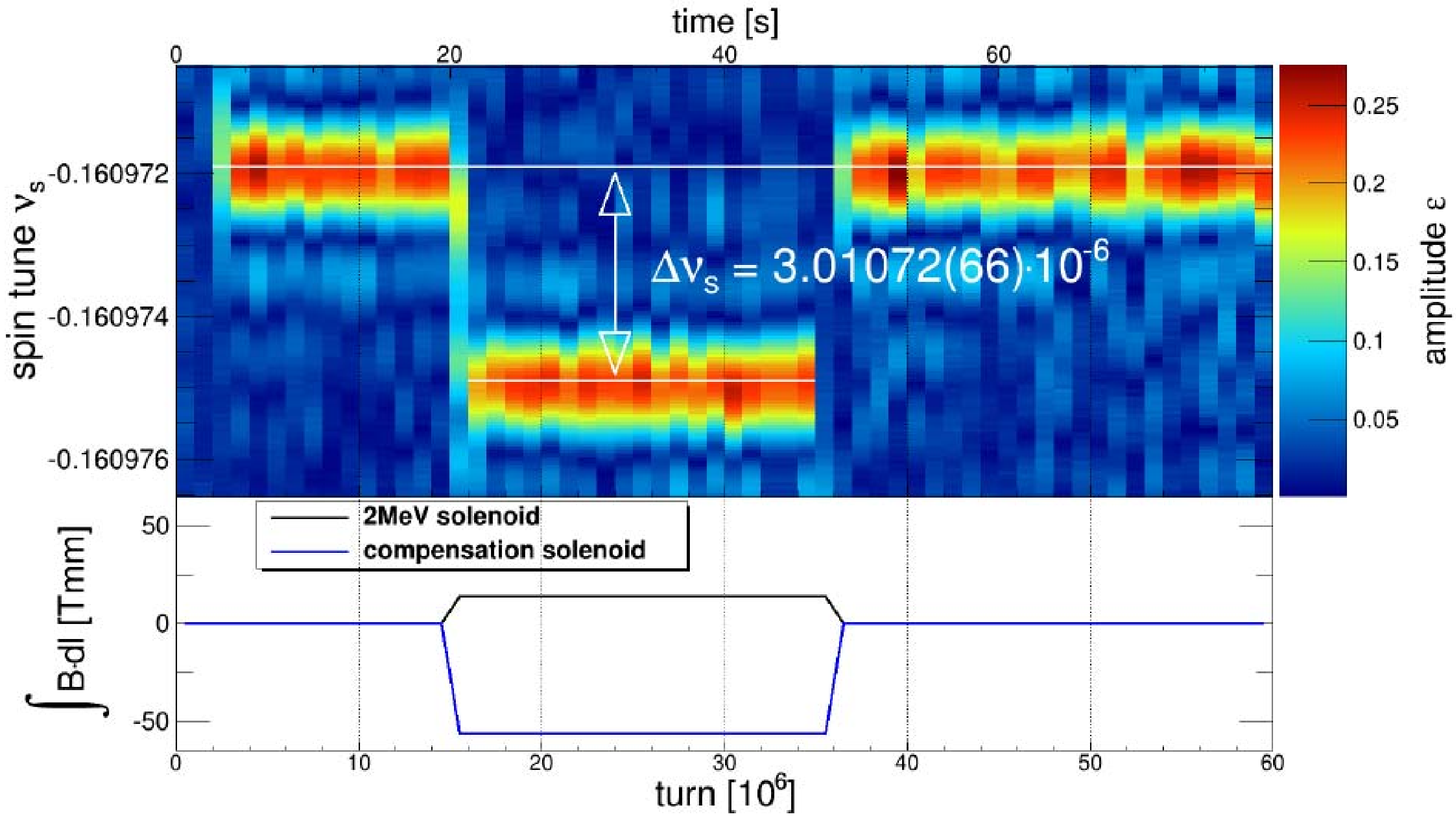


The values of (c_1, c_2), and $(c_3, c_3{}^*)$ depend of spin kicks in non-vertical imperfection fields in the arcs → spin tune perturbed:

$$\nu_s = G\gamma + O(c_1{}^2, c_3{}^2, c_1{}^{*2}, c_3{}^{*2})$$

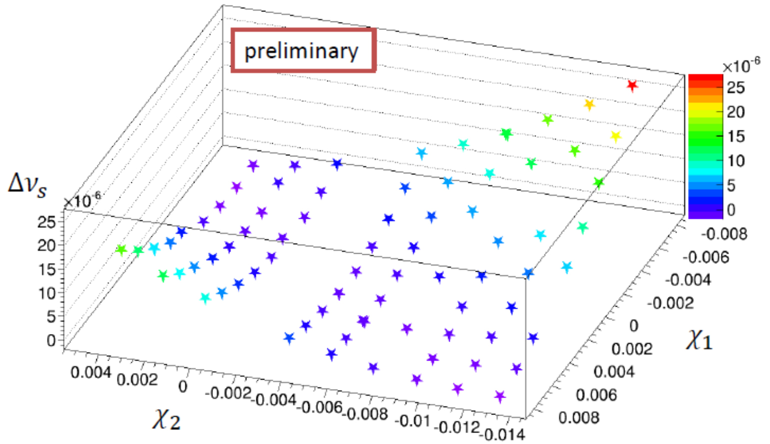
Probe the in-plane imperfection fields by introducing well-known artificial imperfections χ_1 and χ_2.

Systematic study: Measurement of spin tune shift



Take multiple measurements with different χ_1, χ_2, build a spin tune map $\Delta\nu_s(\chi_1, \chi_2)$

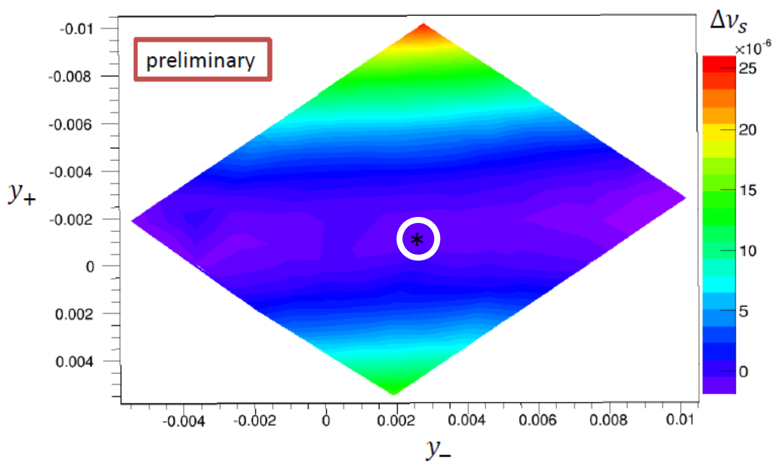
Systematic study: Mapping imperfections



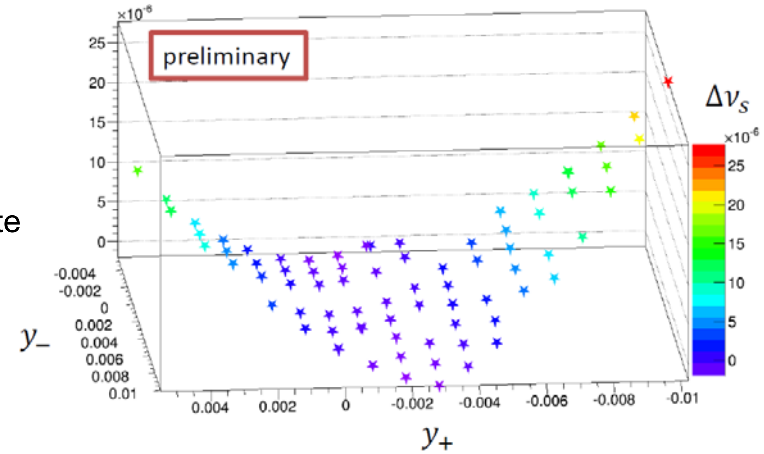
Spin tune map

Map translated to

$$y_+ = \frac{\chi_1 + \chi_2}{2} \qquad y_- = \frac{\chi_1 - \chi_2}{2} \quad \Rightarrow \quad \Delta\nu_s \approx {y_+}^2, {y_-}^2$$



$\Leftarrow$ Fit map to locate saddle point



Spin tune mapping allows experimental reconstruction of spin closed orbit $\vec{n}_{co}$ in storage ring with unprededented precision

Challenges: Overview

Charged particle EDM searches require the development of a **new class of high-precision machines** with mainly electric fields for bending and focussing.

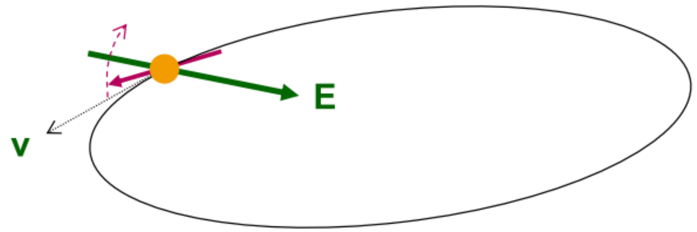
Issues are:

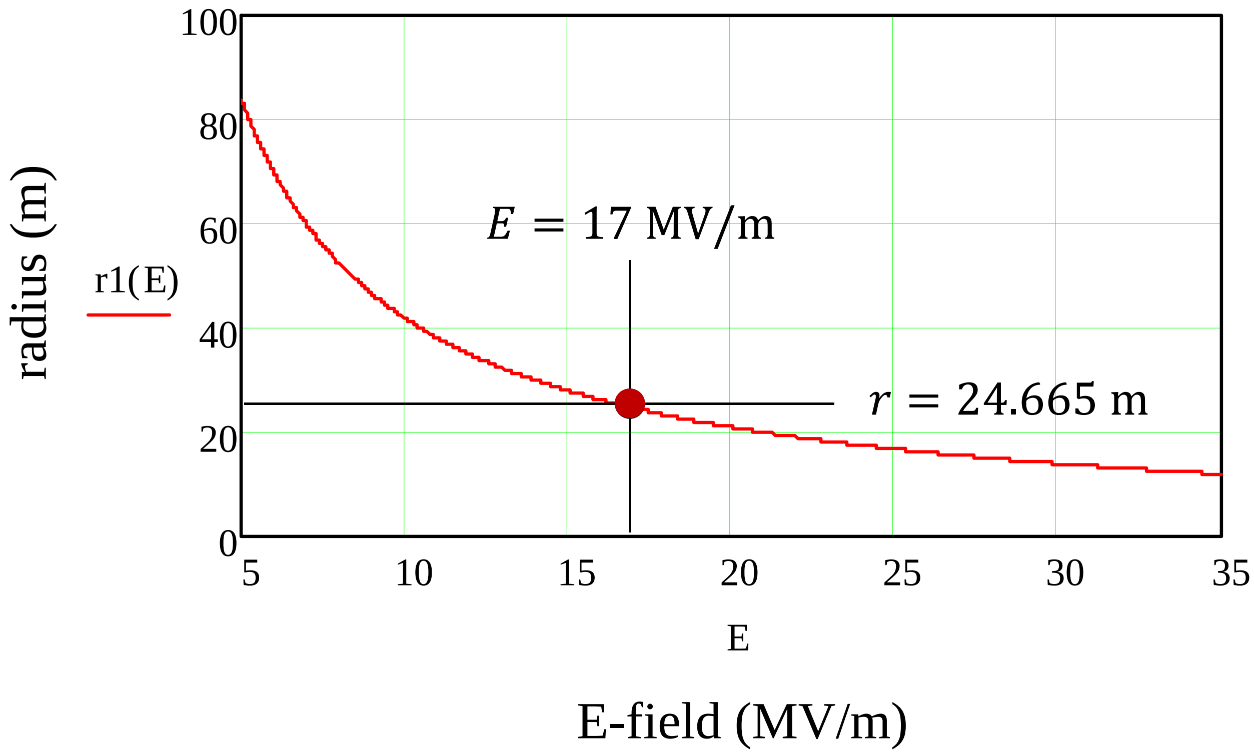
- **Electric field gradients** $\left(\sim 17\,\frac{\mathrm{MV}}{\mathrm{m}}\right)$ at $\sim 2\ \mathrm{cm}$ plate distance
- **Spin coherence time** $(\geq 1000\ \mathrm{s})$
- **Continuous polarimetry** $(< 1\ \mathrm{ppm})$
- **Beam position monitoring** $(10\ \mathrm{nm})$
- **Spin tracking tools**

These issues must be addressed *experimentally* at existing facilities

Challenge: Electric field for magic rings

Protons: Radial E field only



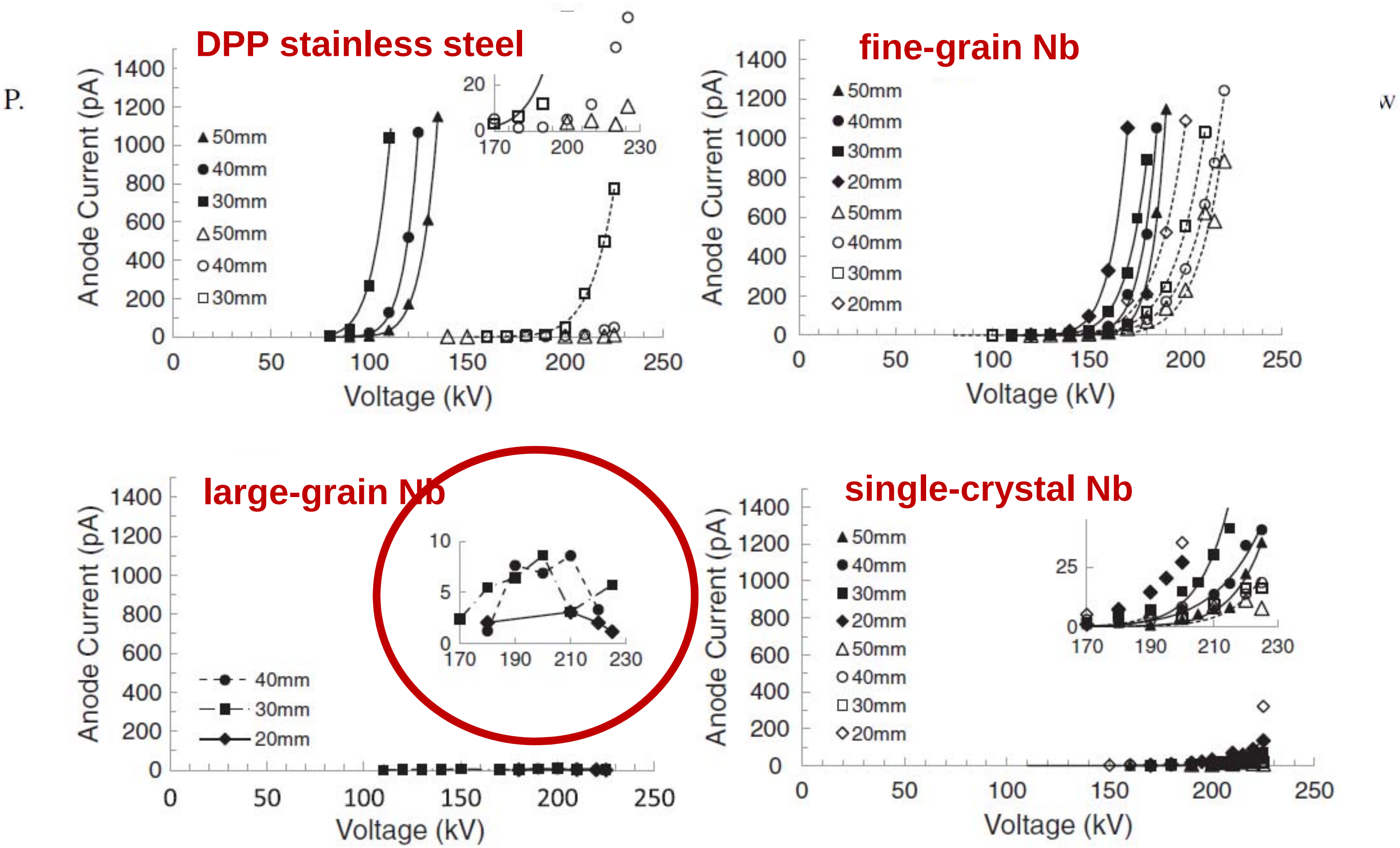


Challenge to produce large electric field gradients

Challenge: Niobium electrodes

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 15, 083502 (2012)

Evaluation of niobium as candidate electrode material for dc high voltage photoelectron guns



Large-grain Nb at plate separation of a few cm yields ~20 MV/m

Challenge: Electric deflectors for magic rings

Electrostatic separators at Tevatron were used to avoid unwanted $\bar{p}p$ interactions
Electrodes made from stainless steel

Routine operation at $1\ \mathrm{spark/year}$ at $6\ \mathrm{MV/m}$

May 2014: Transfer of separator unit plus equipment from FNAL to Jülich

Need to develop new electrode materials and surface treatments

Timeline: Stepwise approach towards all-in-one machine

Step	Aim / Scientific goal	Device / Tool	Storage ring
1	Spin coherence time studies	Horizontal RF-B spin flipper	COSY
	Systematic error studies	Vertical RF-B spin flipper	COSY
2	COSY upgrade	Orbit control, magnets, …	COSY
	First direct EDM measurement at $\mathbf{10^{-2?}\,e{\cdot}cm}$	RF-E(B) spin flipper	Modified COSY
3	Built dedicated all-in-one ring for p, d, $^3\mathrm{He}$	Common magnetic-electrostatic deflectors	Dedicated ring
4	EDM measurement of p, d, $^3\mathrm{He}$ at $\mathbf{10^{-29}\,e{\cdot}cm}$		Dedicated ring

Time scale: **Steps 1 and 2: $<$ 5 years**

Steps 3 and 4: $>$ 5 years

JEDI Collaboration

- **JEDI** = **J**ülich **E**lectric **D**ipole Moment **I**nvestigations

May the force be with us!

- ~ 100 members (Aachen, Dubna, Ferrara, Indiana, Ithaka, Jülich, Krakow, Michigan, Minsk, Novosibirsk, St Petersburg, Stockholm, Tbilisi, … http://collaborations.fz-juelich.de/ikp/jedi/)
- ~ 10 PhD students

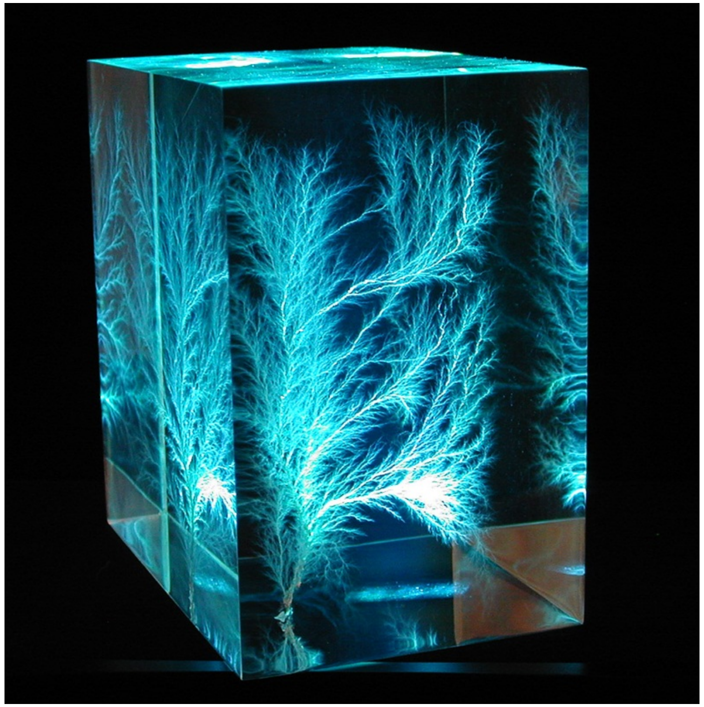
Conclusion

- EDMs offer new window to disentangle sources of CP violation, and to explain matter-antimatter asymmetry of the universe.
- First direct EDM measurements (p, d) at COSY $(\sim 10^{-19}\ \mathrm{e \cdot cm}) < 2018$
- Development of a dedicated EDM storage ring
    - $10^{-29}\ \mathrm{e \cdot cm}$
    - Conceptual design report 2018
- Spin tune determination emerges as novel precision tool for accelerators
    - Allows mapping magnetic imperfections in a machine
- Development of high-precision spin tracking tools, incl. RF structures.
- Development of electrostatic deflectors (also $E_r \times B_y$), BPMs etc.

srEDM experiments are very challenging …,

but the physics is fantastic.

Georg Christoph Lichtenberg (1742-1799)



“Man muß etwas Neues machen, um etwas Neues zu sehen.”

**“You have to make (create) something new,
if you want to see something new”**

Publications

Experiment:

1. A. Lehrach, B. Lorentz, W. Morse, N.N. Nikolaev, F. Rathmann, ***Precursor Experiments to Search for Permanent Electric Dipole Moments (EDMs) of Protons and Deuterons at COSY***, e-Print: arXiv:1201.5773 (2012).
2. N.P.M. Brantjes et al., ***Correcting systematic errors in high-sensitivity deuteron polarization measurements,*** Nucl. Instrum. Meth. A664, 49 (2012), DOI: 10.1016/j.nima.2011.09.055
3. P. Benati et al., ***Synchrotron oscillation effects on an rf-solenoid spin resonance***, Phys. Rev. ST Accel. Beams 15 (2012) 124202, DOI: 10.1103/PhysRevSTAB.15.124202.
4. Frank Rathmann, Artem Saleev, N.N. Nikolaev [JEDI and srEDM Collaborations], ***The search for electric dipole moments of light ions in storage rings,*** J. Phys. Conf. Ser. 447 (2013) 012011, DOI: 10.1088/1742-6596/447/1/012011.
5. Z. Bagdasarian et al., ***Measuring the Polarization of a Rapidly Precessing Deuteron Beam,*** Phys. Rev. ST Accel. Beams 17 (2014) 052803, DOI: 10.1103/PhysRevSTAB.17.052803.
6. F. Rathmann et al. [JEDI and srEDM Collaborations], ***Search for electric dipole moments of light ions in storage rings,*** Phys. Part. Nucl. 45 (2014) 229, DOI: 10.1134/S1063779614010869.
7. D. Eversmann et al. [JEDI Collaboration], **New method for a continuous determination of the spin tune in storage rings and implications for precision experiments,** eprint arXiv:1504.00635 (2015)

Theory:

J. Bsaisou, J. de Vries, C. Hanhart, S. Liebig, Ulf-G. Meißner, D. Minossi, A. Nogga, A. Wirzba, ***Nuclear Electric Dipole Moments in Chiral Effective Field Theory,*** Journal of High Energy Physics 3, 104 (2015), DOI:10.1007/JHEP03(2015)104